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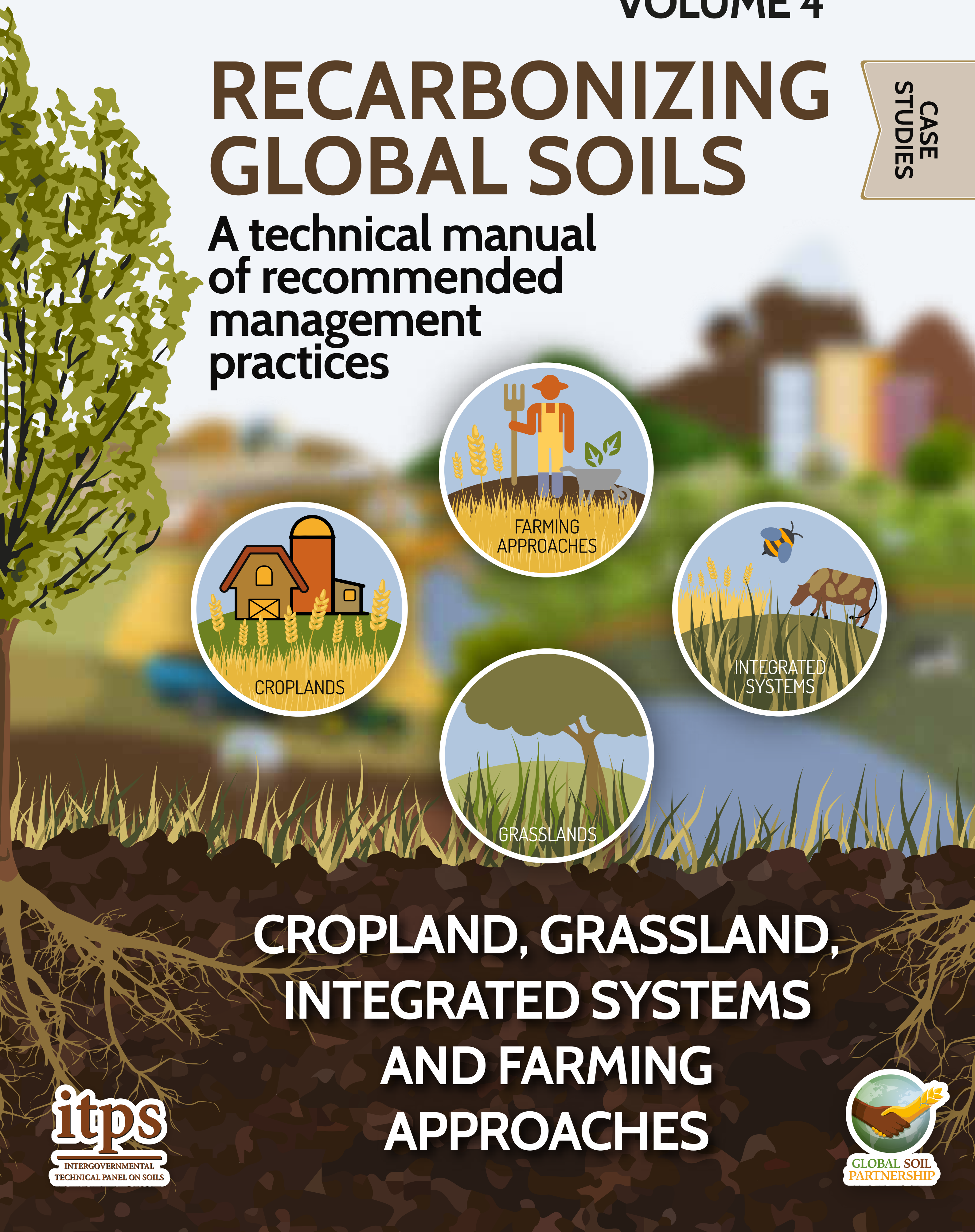
VOLUME 4

RECARBONIZING GLOBAL SOILS

A technical manual of recommended management practices

CASE STUDIES



CROPLAND, GRASSLAND, INTEGRATED SYSTEMS AND FARMING APPROACHES

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GLOBAL SOIL
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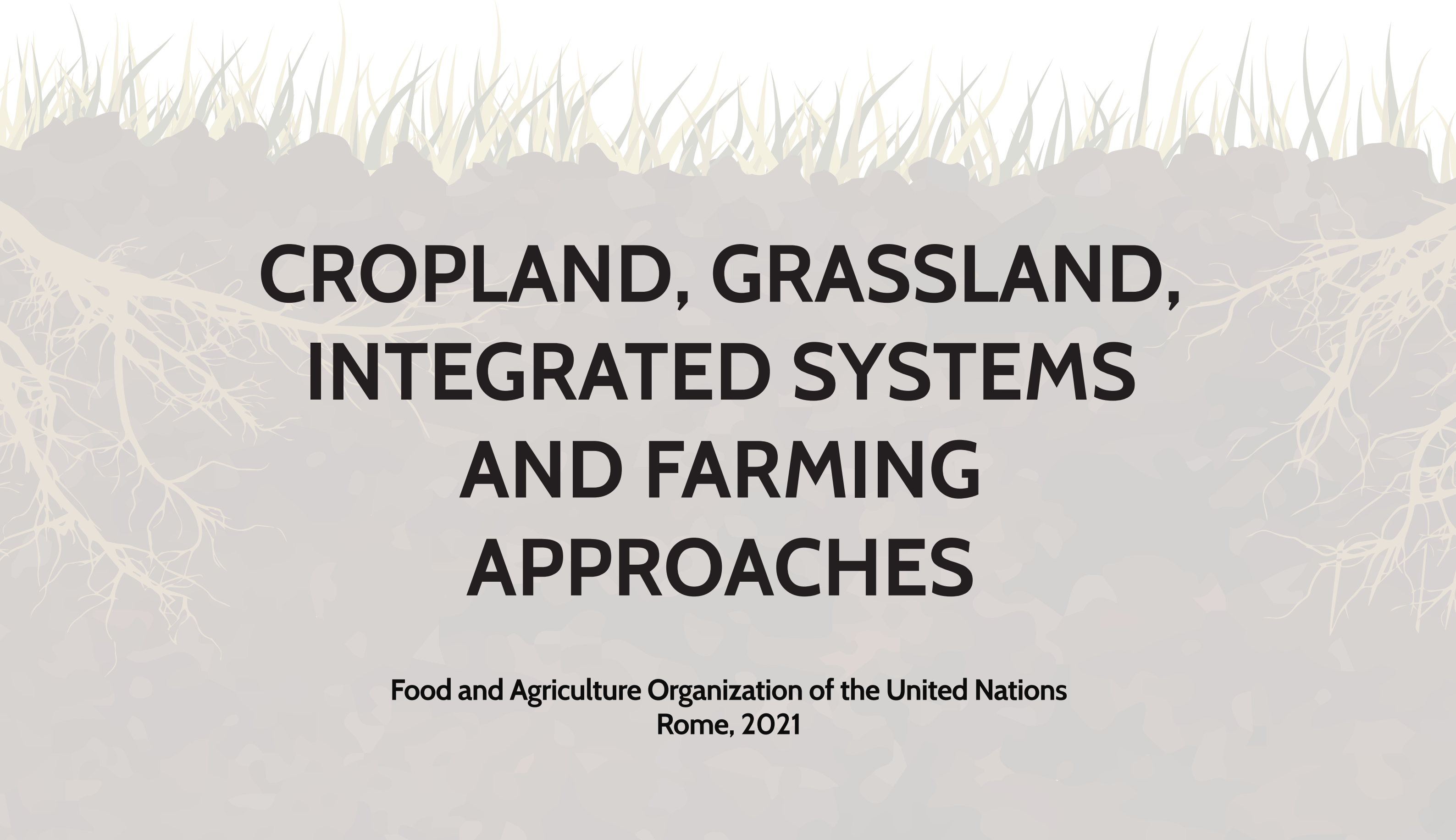

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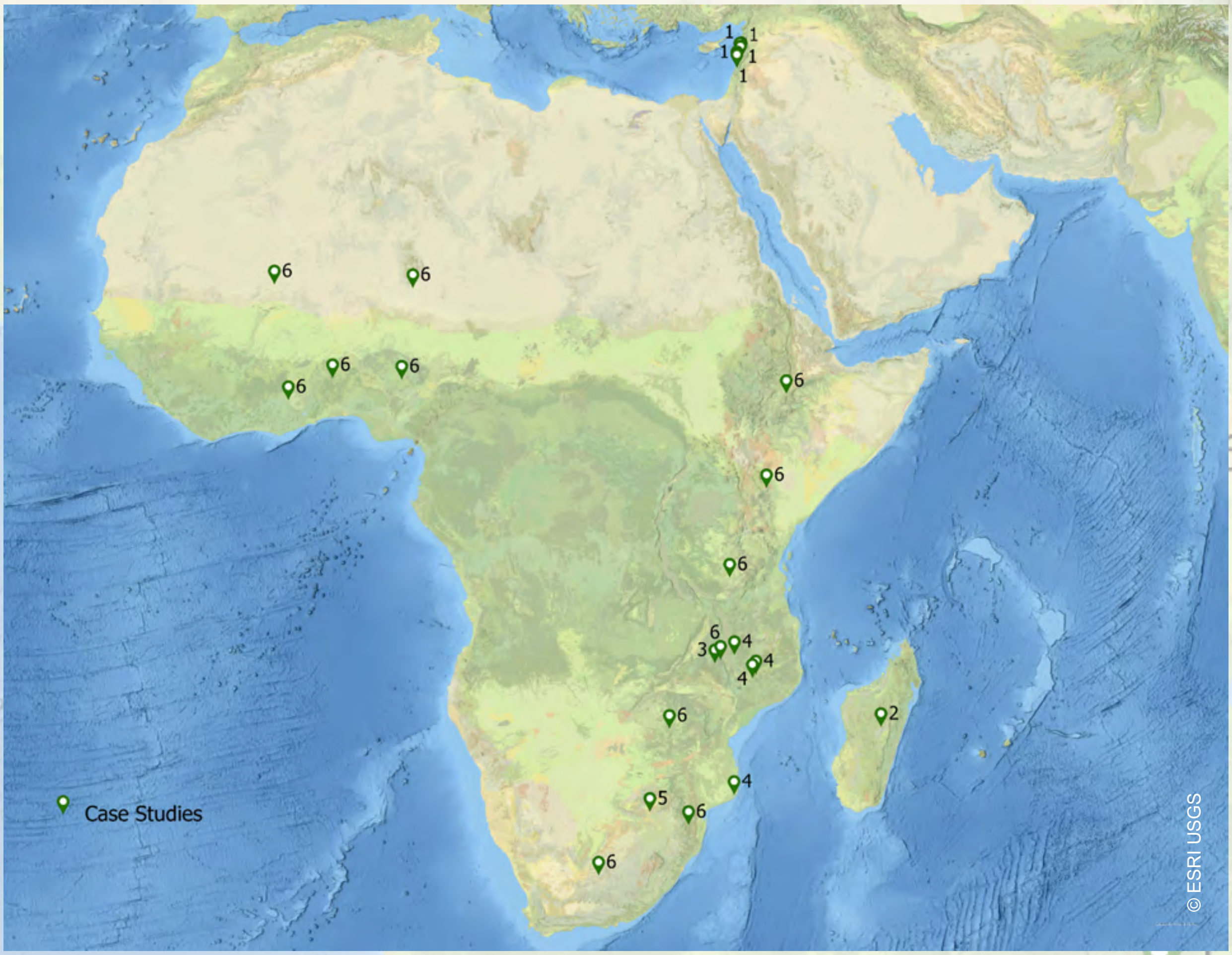
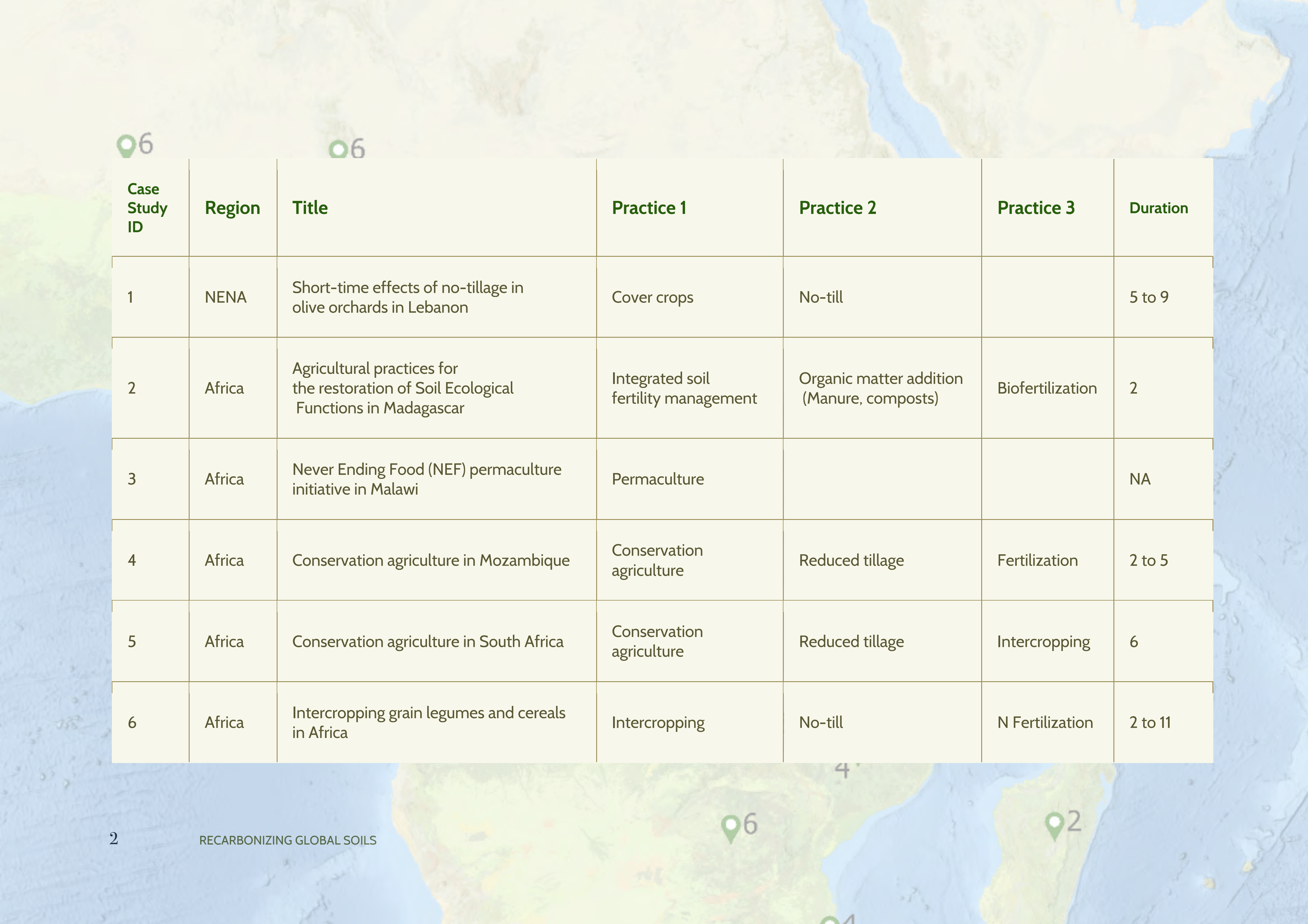


Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
1	NENA	Short-time effects of no-tillage in olive orchards in Lebanon	Cover crops	No-till		5 to 9
2	Africa	Agricultural practices for the restoration of Soil Ecological Functions in Madagascar	Integrated soil fertility management	Organic matter addition (Manure, composts)	Biofertilization	2
3	Africa	Never Ending Food (NEF) permaculture initiative in Malawi	Permaculture			NA
4	Africa	Conservation agriculture in Mozambique	Conservation agriculture	Reduced tillage	Fertilization	2 to 5
5	Africa	Conservation agriculture in South Africa	Conservation agriculture	Reduced tillage	Intercropping	6
6	Africa	Intercropping grain legumes and cereals in Africa	Intercropping	No-till	N Fertilization	2 to 11



1. Short-time effects of no-tillage in olive orchards in Lebanon

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1. Related practices and hot-spot

No-tillage, cover crops; Dryland

2. Description of the case study

The effect of no tillage on the build-up of the soil organic carbon (SOC) was evaluated in olive orchards in sub-humid Mediterranean conditions. The studied fields covered nine series: four from North-Lebanon, three from Mount-Lebanon and two from South-Lebanon. Each series consisted of three olive orchards treated by conventional tillage (Photo 1), no-till with cover crops: vetch (*Vicia sativa*) (Photo 2) or spontaneous vegetation (Photo 3) or herbicide application. Woodlands covered by native oak/pine trees, selected from the proximity of the orchards, were considered as a control. From each orchard, composite soil samples were collected from two depths (0-10 cm and 10-30 cm). The comparison of soil organic carbon by pairs showed no difference between the no-till treatment and the undisturbed woodland, on one hand, and between olive orchards managed by tillage, no-till and herbicide application, on the other. No-till plots could be considered in an intermediate position between the tilled plots and the woodlands. This practice may not have been used for long enough (≈5 years) to allow a substantial build-up of SOC. In addition, the SOC in the humified fraction, associated with the fine mineral particles (<50 µm), was determined. This protected fraction could be the main cause for the enrichment of SOC in no-till systems. The humified SOC, plotted against the SOC in bulk soil, showed a slight increase in the no-till plots (57.2% of SOC) as compared to the conventional treatment (42.9% of SOC). The absence of disturbances caused a vertical stratification in the upper soil. In soils occupied by native vegetation 43 percent of the C stocks were in the top 10 cm, against 37 percent of the stocks in orchards. Further, stocks of organic carbon (0-30 cm) increased by 0.83 tC/ha/yr in the no-till orchards. Despite this short-term build-up, the stocks in these conservation plots were 20 percent smaller than in the woodlands.

3. Context of the case study

Olive (*Olea europea* L.) holds a major place in Lebanese agriculture. The cultivated area of olives is estimated to be 563 km^2, which represents 8 percent of the total agricultural land (IDAL, 2014). Mostly rainfed, olive orchards are present in all governates from north to south with a recent expansion as irrigated in northern Bekaa valley (Verner *et al.*, 2018). Orchards located at altitude may be subject to erosion, and thus to a deterioration of the soil quality and structure. In addition, the use of agricultural machinery is rather difficult in haphazard relief and narrow terraces. In these conditions, and hence the practice of no-till might be convenient and beneficial. The trial started on 4 ha in 2007/08, on area under no-till and its size increased to 562 ha the following season. This approach was tried in combination with leguminous cover crops in olive orchards in the Syrian Arab Republic and Lebanon (Jouni *et al.*, 2012).

This case study was conducted in warm temperate dry climatic conditions (sub-humid east Mediterranean) characterized by 800 mm of annual rainfall and an annual temperature close to 18 °C. Soils types were Luvisol, Regosol and Cambisol. Orchards treated by no-till were compared to those managed conventionally (tilled twice or three times a year). The comparison was undertaken by pairs from the same location (similar soil type and environmental conditions). In seven pairs out of nine, carbon stocks increased under no-till, as compared to tilled orchards. Following a short-term practice of no-till, associated with overwinter cover crops, this study aimed at studying changes in soil organic carbon. SOC were evaluated in olive orchards managed by no-till with cover crops, no-till with herbicides application, and conventional tillage. Soils from undisturbed woodlands served as a reference (Figure 1).

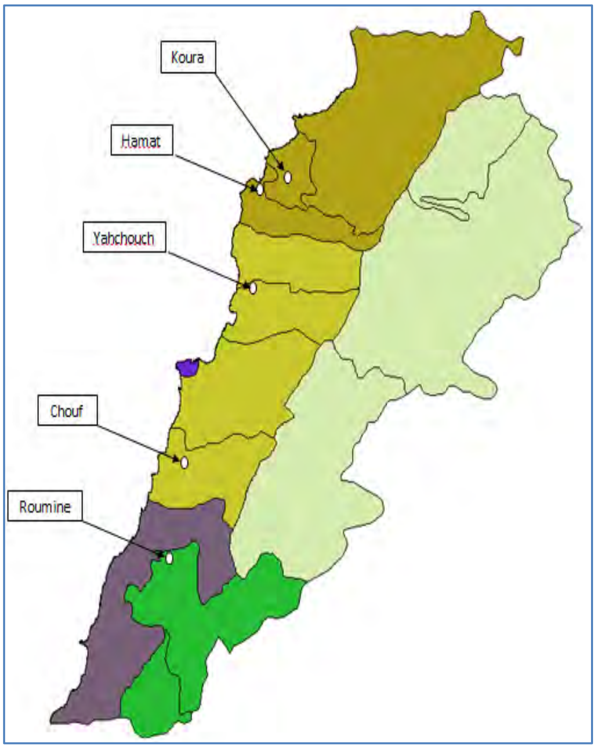

Figure 1. Map of Lebanon showing the sites occupied by olive orchards and included in the study of soil organic carbon.

Source: Thérèse Atallah, Marie Nabhan, Souzi Rouphael

4. Possibility of scaling up

The application of herbicides, combined with no-tillage, is a practice started some 40 years back, in large plains occupied by olive orchards. This approach was adopted on economic grounds (savings in fuel, labor etc.) and was considered as a modern innovative practice. Scaling up of no-till with cover crops is certainly possible, both in olive and fruit orchards. But in no-till, the soil needs to remain covered by spontaneous vegetation or by cover crops. This may seem difficult to accept by farmers and professionals, on cultural and economic grounds. Farmers and managers fear the consequences of such a practice. In their minds, this might be 'harmful' to the soil properties especially the aeration. Another problem often linked with no-till is the thriving of weeds, especially perennials. Growers consider this as a poor practice and may reflect negatively on their skills as land managers. Also, the termination of cover crops requires devices, such as a shredder, that may not be available. This and the cost of seeds may be considered as barriers for adoption by growers.

5. Impact on soil organic carbon stocks

The baseline C stock was 58.7 t/ha in the upper 30 cm of tilled orchards, while the stock reached 62.5 t/ha in those managed by no-till (Table 1). This increase of 0.76 t/ha/yr was obtained over a short-term (*circa* 5 years) management. When separating the soil depths into 0-10 and 10-30 cm, the amounts of $SOC_{0\text{-}10\ cm}$ were 21.2 to 23.2 t/ha in orchards and 34.1 t/ha in woodlands. In the deeper level, values of $SOC_{10\text{-}30\ cm}$ ranged between 36-39 t/ha against 45 t/ha in the soils occupied by native vegetation. This indicates a potential to increase C storage, equal to some 12 t/ha in the top 10 cm, and to 9 t/ha in the 10-30 cm depths.

Table 1. Carbon stocks obtained in olive orchards

Soil type	C stock (tC/ha)			Duration (Years)	Additional C storage (tC/ha/yr)	Depth (cm)	C stock in undisturbed woodland (tC/ha)
	Tillage	No-tillage with cover crops	Herbicide application				
Luvisol Regosol Cambisol	58.7	62.5	57.6	5	0.76	0-30	79.3

Olive orchards managed by conventional tillage (baseline) no-tillage or by herbicide application, and in undisturbed woodland, under warm temperate dry climatic conditions in Lebanon

6. Other benefits of the practice

6.1 Improvement of soil properties

Reduced soil disturbances may hasten the building-up of SOC in olive orchards. This could be an important step in promoting carbon sequestration and offsetting the effects of greenhouse gases, generated by Lebanese population in sectors such as power generation, transportation (MoE/UNDP/GEF, 2015). Other beneficial aspects may be an improved soil moisture retention (Jouni *et al.*, 2012), and a reduction of the impact of rain drops on soil surfaces (Gómez *et al.*, 2018) through greater infiltration.

Some effects on soil nutritional status may be observed. Nutrients are absorbed by the cover crop and recycled minimizing the losses, and hence reducing the nutrients inputs to the olive trees. In addition, the reduced disruption of soil aggregates may promote soft-bodied soil microarthropods. Considered as biological indicators of soil quality, soil microarthropods increased in the absence of tillage in these olive orchards (Jdid, 2014).

6.2 Minimization of threats to soil functions

Table 2. Soil threats

Soil threats	
Soil erosion	This aspect was not evaluated in this case study, but cover crops reduced soil loss in Spanish olive orchards as compared to those under bare soil and managed by conventional tillage (Gómez *et al.*, 2018).
Nutrient imbalance and cycles	Improved nutrient cycling through the uptake by cover crops of available N, P and K in soils overwinter. This is especially applicable to non-legume cover crops (Rouphael *et al.*, 2019). Fields under no-till presented an increase in soil organic matter, phosphorus and potassium contents. The benefits were cumulative in relation to years of implementation (Jouni *et al.*, 2012).
Soil pollution	In a previous work on overwinter cover crops, nitrate leaching was reduced if a non-legume or a mixture of two species (one legume plus one cereal) is present (Rouphael *et al.*, 2019). Elsewhere in Sicily, cover crops grown as buffer strips provided a useful means of managing soil nitrate (Novara *et al.*, 2013).
Soil biodiversity loss	In parallel to the study of soil organic carbon, an enumeration of soil microarthropods was conducted. The reduction in soil disturbances increased soil microarthropods especially the soft-bodied ones (Jdid, 2014).
Soil water management	An earlier work under no-till with a cover crop (vetch essentially) showed an increase in soil moisture (Jouni *et al.*, 2012), an important soil property in rainfed orchards.

6.3 Increases in production (e.g. food/fuel/feed/timber)

Allowing soil surface to be covered by overwinter vegetation may be beneficial at another level. Herds of sheep or goat (or even laying hens) may be allowed to roam freely in the orchards grazing the surface vegetation. This practice was tested in mountainous inland area of Lebanon (anti-Lebanon region) with cover crops planted beneath rainfed cherry trees (Darwish *et al.*, 2012). In addition to providing free grazing ground to small ruminants, these feeding animals help by shortening the growing vegetation, making it easier to shred later.

In this trial and as olive production presents an alternate bearing, there was insufficient time to make observations on yield. Other researchers have found in long-term experiments a potential risk of yield decrease (Gómez, 2017).

6.4 Mitigation of and adaptation to climate change

In Lebanon, the contribution of the agricultural sector to emissions of greenhouse gases (GHG) is minor (3.6 percent of global emissions). Still, sustainable practices may be introduced in order to alleviate the effects of climate change, such as droughts. In fact, conservation agriculture and the switching to fertigation and drip irrigation were recommended as mitigation options (MoE/UNDP/GEF, 2015).

6.5 Socio-economic benefits

- Reduced addition of fertilizers due to better nutrients cycling
- Improved water management and its effect on rainfed olive production
- Reduced expenses related to tillage, weed control
- Gain related to potential grazing of small ruminants.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 3. Soil threats

Soil threat	
Soil water management	No evidence of competition between the main crop and the cover crops was found. The reason for this is the fact that olive is rainfed and the cover crop is terminated relatively early. As such, the cover crop may retain higher moisture in soils.

7.2 Increases in greenhouse gas emissions

Authors have discussed the issue of possible promotion of GHG emissions with cover crops. Globally, by recycling nitrogen these crops might be reducing the risk of denitrification. In fact the use of both legume and non-legume cover crops was found to maximize agronomic efficiency without increasing cumulative or yield-scaled nitrous oxide losses in irrigated maize under Mediterranean conditions (Guardia *et al.*, 2016).

7.3 Conflict with other practices

The conflict is more in the willingness of growers to reduce tillage. Olive orchards may be tilled twice or three times per year. The objectives are the promotion of good soil aeration and the control of weeds. The occurrence of 'weeds' is not considered compatible with good managerial practices. For this, the application of herbicides was adopted relatively easily, especially in larger orchards. Also, severe weeds infestation was witnessed as part of conservation agriculture (Chalak *et al.*, 2017).

7.4 Decreases in production (e.g. food/fuel/feed/timber/fibre)

There should no negative impact on olive production or on water balance, as long as the cover crop is terminated at the right time and managed properly.

7.5 Other conflicts

One constraint mentioned by a landowner (Bassil D., personal communication) who was trying it, is the drying out of the cover vegetation in late spring/summer/early fall. This makes the field more liable to fire, a serious danger encountered in Mediterranean countries in late summer.

8. Recommendations before implementing the practice

A build-up of knowledge is recommended. This includes:

- the choice of cover crops species and its availability
- the best practices (sowing time, termination time and method)
- devices used for this practice
- a demonstration of the effects on soil and crop properties.

9. Potential barriers for adoption

Table 4. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Know-how needed about the sowing of cover crops and its termination. Machinery or devices used for this could be shredders with a very shallow incorporation of the plant material.
Social	Yes	There is a lack of willingness (Chalak *et al.*, 2017) due to a number of issues, especially the perception of no-tillage by farmers.
Economic		
Institutional	Yes	Lack of support and promotion by extension services
Legal	No	Olive growers are in general owners of their fields, so the legal right is not applicable.
Knowledge	Yes	See section 7.6.

Photos

Photo 1. Tilled olive orchard in South Lebanon

Photo 2. Vetch (Vicia sativa) covering the ground of an olive orchard in North Lebanon (left) in April 2014.

Observation of mature pods of vetch within the same field (right) much later in the season. Vetch has the ability to self-reseed itself, once

Photo 3. Spontaneous vegetation in an olive orchard, in south Lebanon, attracts beneficial insects

Acknowledgements

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2. Agricultural practices for the restoration of soil ecological functions in Madagascar

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1. Related practices and hot-spot

Integrated soil fertility management, Organic fertilization (manure, (vermi) compost), Mineral fertilization Biofertilization, Earthworm inoculation

2. Description of the case study

With agroecology, great attention is now given to ecological processes occurring within agrosystems. Nevertheless, little attention has been given to soil ecological processes and the below-ground biodiversity in agricultural practices despite their recognized high potential to enhance ecosystem service delivery and promote multiple ecosystem functions simultaneously (Ratnadass, Blanchart and Lecomte, 2013; Clermont-Dauphin *et al.*, 2014; Blanchart *et al.*, 2020). Soil function restoration (SFR) is especially relevant for tropical smallholder farmers developing their crops on fragile and poor soils, with low available chemical inputs and under climate change. Restoring soil functions first requires restoring the abiotic environment or habitat and providing energy to soil biota. SFR practices gather (i) the use of original organic inputs with high agroecological performances such as vermicomposts, composts, improved manures, (ii) an efficient combination of organic and mineral inputs promoting plant functions, (iii) biofertilization (i.e. inoculation of soil-plant mutualists (such as earthworms, mycorrhizae, etc.) to restore some soil functions) and (iv) the use of crop varieties that respond efficiently to innovative SFR practices.

Understanding and managing the plant-soil interactions and feedbacks in agricultural transition is thus challenging. A key question is what agronomic interventions are required for successful restoration of soil functions in agroecological agrosystems? In Madagascar, different practices based on combined fertilization practices and co-designed with farmers have been tested in the frame of a project called SECuRE (Soil ECological function REstoration to enhance agrosystem services in rainfed rice cropping systems in agroecological transition, funded by Agropolis Fondation, 2017-2020). The agronomic, socio-economic and ecological performance of practices have been assessed through the measurements of many parameters and through knowledge exchange with farmers. A participatory approach has also been designed to help researchers to better understand farmers' perception and drivers for decisions regarding soil fertility and to help farmers to better understand the trial protocol and the results.

3. Context of the case study

The experiment was conducted in the Itasy region, Madagascar, near the city of Arivonimamo, 40 km West of Antananarivo (GPS coordinates: 19°03′14.3″S 47°15′24.5″E). The region is about 1 400 m above sea level. The relief is sloping with the presence of granite mountains and rock outcrops. The climate has two very distinct seasons: a hot and humid season from October to March and a cool, dry season from April to September. The region is characterized by a mean annual temperature of 18°C and a mean annual rainfall of 1 300 mm. The soils are red to brown ferrallitic strongly desaturated soils (i.e. Ferralsols in the FAO classification), with about 40 percent clay, 20 percent silt and 40 percent sand in the upper layer. They are rich in gibbsite. The iron and aluminum oxide contents are high (31.4 percent Fe_2O_3 and 28.2 percent Al_2O_3) while those of silica are low (10 percent SiO_2). The soil pH is in the range 4.7-5.1. Soil carbon contents are low (total C = 29 g/kg). Nutrient omission trials on rice growth have shown strong deficiencies in the decreasing order: phosphorus > calcium > magnesium > nitrogen (Raminoarison *et al.*, 2020). Phosphorus (P) is a major limiting nutrient because of the low content of soil organic matter (and consequently low organic P content) and the high P-sorption potential of soils.

The cultivated areas in the region are mainly concentrated in lowlands, which represent nearly half of cropped areas. The bottoms of slopes are also intensively cultivated (more than a quarter of the cultivated areas). Steep and weak slopes as well as the top flats represent a weaker area for cultivation in the region. Lowland rice (*Oryza sativa*) cultivation is the main crop. It is generally practiced in rotation with vegetable crops in the same year. Lowland areas are saturated due to permanent cropping. Currently rainfed cultivation of rice and other grains or tubers on upland soils (slopes) only represents a small proportion of cultivated areas. Nevertheless, due to the need to produce more of this staple crop, upland cultivation of rice faces many constraints such as a poor soil fertility, the presence of pests and pathogens, and high cost of fertilizers. Family farms present on average an area of 91 acres (70 percent lowland and 22 percent upland). This chapter deals with upland rice and not with lowland rice (including SRI, System of Rice Intensification).

4. Possibility of scaling up

In this experiment, we tested different types of amendments, fertilizers, beneficial organisms, in the form of combined management practices to improve soil ecological functions and plant response (production and yield). Organic, mineral and biological substrates were chosen in agreement with farmers, substrates being - more or less - available on farms or in the neighboring areas. This participatory approach and the generic characteristics of Ferralsols in the tropical regions make the results of this study easily transferable to other parts of the world, especially in West Africa, South America and South-East Asia. The main result of our study is that combining organic and mineral matter can increase soil ecological functions and the provision of several agrosystem services such as C sequestration, nutrient recycling, and plant growth, nutrition, yield and resistance to disease. All results are available on the website (in French) of the project (www.secure.mg). Dissemination of innovative sustainable practices to smallholder farmers will be co-constructed at the scale of Malagasy Highlands, and could be realized at a larger scale to improve food security and farmer livelihoods in sub-Saharan Africa where soil and farmers′ constraints are similar to Malagasy Highlands: fragile and poor soils, low access to chemical fertilizers, small farms, etc.

5. Impact on soil organic carbon stocks

Soil carbon contents and stocks have been measured after two cropping seasons in our experiment (i.e. 2 years). Soil carbon content was measured for 24 samples per treatment with the Walkley-Black method, after air-drying of soil samples. Bulk density was measured with a cylinder of a known volume (10 cm depth) with 8 replicates per treatment; soil was oven-dried at 105 °C and weighed. Soil C stocks were calculated on a volume basis as follows:

$$\text{Soil C stock (tC/ha)} = \text{C content (g/kg)} \times \text{bulk density (t/m}^3\text{)} \times \text{d (layer thickness, m)} \times 10.$$

The baseline C stock was measured in the control (no fertilization) and was equal to 28.66 tC/ha (upper 0-10 cm). C stocks were also measured in 15 other practices differing in fertilization. Data are still unpublished while available on the SECuRE website (www.secure.mg). Tested practices are referred to SFR (Soil Function Restoration practices), from SFR1 to SFR16 (Table 5), with SFR16 being the negative control without fertilization. C storage was calculated as the difference between SFR and SFR16 (synchronic approach).

Table 5. Mean additional C storage (tC/ha/yr) for different treatments

More information on the practice	Additional C storage (tC/ha/yr)
SFR1: 3 t/ha cattle soil-mixed powder	0.25 ± 1.7
SFR2: 3 t/ha manure	0.99 ± 1.0
SFR3: 3 t/ha manure + 40 kg/ha NPK	1.18 ± 1.9
SFR4: 6 t/ha manure	1.30 ± 1.4
SFR5: 6 t/ha nitrogen-conserved manure	0.78 ± 2.1
SFR6: 6 t/ha compost	2.24 ± 3.2
SFR7: 6 t/ha vermicompost	1.15 ± 1.7
SFR8: 100 kg/ha NPK + 100 kg/ha urea	0.94 ± 2.9
SFR9: 6 t/ha manure + 500 kg/ha dolomite	0.23 ± 0.5
SFR10: 6 t/ha manure + 500 kg/ha ashes	0.86 ± 2.3
SFR11: 6 t/ha manure + 500 kg/ha hyperphosphate	0.93 ± 2.2
SFR12: 2 t/ha manure + 2 t/ha compost + 2 t/ha vermicompost	0.97 ± 1.7
SFR13: 2 t/ha manure + 2 t/ha compost + 2 t/ha vermicompost + 500 kg/ha ashes	0.80 ± 2.1
SFR14: 2 t/ha manure + 2 t/ha compost + 2 t/ha vermicompost + 500 kg/ha hyperphosphate	0.71 ± 2.4
SFR15: 2 t/ha manure + 2 t/ha compost + 2 t/ha vermicompost + 500 kg/ha guano	1.11 ± 2.3

Calculated as a difference with the control treatment without fertilization in the 2-year experiment

Results show that the C storage potential is very variable and more important for high inputs of compost (SFR6, 6 t/ha) with mean additional C storage above 2 tC/ha/yr. High inputs of manure (SFR4) and vermicompost (SFR7) are also potentially interesting for C storage (above 1 tC/ha/yr) along for the complex fertilization with guano (SFR15).

6. Other benefits of the practice

6.1. Improvement of soil properties

Physical properties

In our experiment, there was no change in bulk density after 2 years with values around 1.06 g/cm^3. Aggregation (dry sieving) changed a little with some SFR showing an increase in the percentage of macroaggregates compared to the negative control (41.5 percent): 47.5 percent in SFR11, 47.0 percent in SFR6, 46.5 percent in SFR5, 46.0 percent in SFR10, 45.7 percent in SFR13.

Chemical properties

Total soil N content (0-10 cm) strongly increased in many SFR practices, compared to SFR16 (1.55 g/kg): up to 1.83 in SFR6 and around 1.7 for SFR4, SFR5, SFR7, SFR14. Available (extracted with resin) P also increased in all SFR compared to SFR16 (1.04 mg/kg): up to 4.69 in SFR15, 3.8 in SFR11, and around 2.7 in SFR12, SFR13, SFR14.

Biological properties

Microbial biomass, assessed by microbial P content, increased in all SFR, especially in SFR6, SFR4, SFR5, SFR7, SFR12, and SFR13. Soil macrofauna and nematodes were also strongly affected by fertilization: nematode density (in 250 g of soil) was 388 individuals for SFR16 and higher for all SFR especially in SFR10 (1 190), SFR6 (1 432) and SFR15 (1 692). Bacterial-feeding nematodes were especially abundant in SFR9 and SFR10.

6.2 Minimization of threats to soil functions

Table 6. Soil threats

Soil threats	
Soil erosion	Soil losses generally decreased with increase in SOC (Blanchart *et al.*, 2006).
Nutrient imbalance and cycles	Yes, see above for total soil N and exchangeable P
Soil acidification	pH increased with organic fertilization: pH was low in the negative SFR16 and the positive control SFR8; it increased in all other SFR (especially 6-7-9-11-12)
Soil biodiversity loss	See above for macrofauna and nematofauna. We also investigated microbial functions (Ecoplates), tea bags, and bait lamina
Soil compaction	Yes, see bulk density above

6.3 Increases in production (e.g. food/fuel/feed/timber)

Crop yield at the end of the second year of the experiment showed important differences between SFR practices. As expected, yield was very low in the negative control (SFR16) 0.04 t/ha, in the mineral fertilization practice (SFR8) 0.75 t/ha, and in the poor cattle powder (SFR1) 1.03 t/ha. For all other practices, yield exceeded 2 t/ha and exceeded 3 t/ha in SFR4 (highest value 3.59 t/ha), SFR9 and SFR10.

6.4 Mitigation of and adaptation to climate change

NA

6.5 Socio-economic benefits

Two participatory farmers' workshops allowed to evaluate the farmers' perception of the tested practices. Farmers considered 8 main criteria to evaluate the amendments used in the experiment: cost, transport, accessibility, expected effects on soil quality, on rice production, on other crops, on pests, and easiness of spreading. Such diversity of criteria indicates that farmer's decisions are multifaceted, based on economic issues but also on labor-related and agronomic and ecological issues. A rough economic analysis considering the cost of amendments compared to the rice yield for each SFR shows that manure remains the most interesting amendment (relatively high yield and a low cost of manure). The mixing of manure with ashes (SFR10) also gives a high ratio. Due to the high cost of vermicompost sold in the area, all SFR integrating vermicompost presents a relative low ratio despite the high yield measured. This suggests the need to support and train farmers so as they are able to produce vermicompost by themselves so as to increase the amount at local scale and lower the price.

7. Recommendations before implementing the practice

Local availability of organic matters in the area (cattle soil-mixed powder, manure, other biomass needed to elaborate compost and vermicompost) is one of the main limitations. Implementation of new practices based on the use of organic matters would benefit from technical, economic and institutional support. Such support can take the form of a network of skilled farmers, extensionists and advisors, support by decentralized agricultural State agencies, able to produce and sell a high amount of compost or vermicompost and to disseminate exchange experiences and advice to other farmers in the area.

8. Potential barriers for adoption

Table 7. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Need of organic matter to produce compost or vermicompost.
Social	Yes	Trade-off to be made regarding the time and labor needed for organic fertilizer preparation (compost, vermicompost), allocation of the biomass (cattle feeding, compost, even selling of biomass), the cost and the results on agronomic (rice production) and soil ecological issues.
Economic	Yes	Poor farmers from the Highlands in Madagascar have very low access to fertilizers, and even for the poorest, to manure.
Institutional	Yes	Extension and advisory services for farmers are crucial to support technical change. Thus, service providers such as decentralized public organizations, farmer organizations or NGOs must be coordinated to provide accessible, relevant, timely and affordable advice for farmers. In an innovation perspective, technical support is therefore not sufficient, other services must be considered: capacity building, access to market and to credit, support for networking and institutional support for scaling up (Faure *et al.*, 2019).
Legal	Yes and No	Land tenure is highly complex in Madagascar, because of traditional rights intertwined with public rights. However organic fertilizers are easily accepted by the local population because it does not question land transmission (contrary to tree plantations for agroforestry practices).
Knowledge	Yes	Exchanges of knowledge between scientists and farmers are crucial for the adoption of such practices. Local NGOs transfer knowledge to help farmers producing compost of vermicomposts by themselves.
Other: choice of the research model	Yes	The design of the research intervention is highly influential on the use of the research outputs and hence on the biophysical and societal impacts (Faure *et al.*, 2018). Participatory research approach has been chosen in order to bridge researchers' and farmers' knowledge: inclusion of farmers' practices into the trials, identification of farmers' descriptors, matching farmers and researcher's evaluation regarding the performance of the SFR tested, and discussion of the trade-off accordingly. Other research models imply multi-stakeholders' commitment: co-design of innovation, support for the innovation process, and promotion of open innovation.

Photos

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Photo 4. Field experiment at Arivonimamo, Highlands, Madagascar

Sixteen practices have been co-designed to restore Soil Ecological Function (SFR), with 4 replicates. At the bottom left, we can see SFR8 (practice with mineral fertilization only) showing that mineral fertilization with NPK cannot eliminate deficiencies (Ca, Mg). On the right side we can see SFR16 (negative control without fertilization) and the quasi absence of production. Other SFR combined different types of organic matters and mineral matters.

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Photo 5. Preliminary meeting with farmers to exchange knowledge on fertilization and sustainable practices (2018)

This meeting aimed at identifying amendments used by farmers (frequency, availability, cost...) and at collecting their perception (indicators) of soil quality, rice growth, efficacity of amendments.

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3. Never Ending Food (NEF) permaculture initiative in Malawi

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1. Related practice

Permaculture.

2. Description of the case study

Never Ending Food (NEF) is a community-based initiative in Malawi, Africa which uses Permaculture design to address developmental issues of food/nutrition security, poverty reduction, climate change, and sustainable agriculture. Permaculture is a term coined in Australia in the 1970s from the combination of the two words *permanent* and *agriculture*. It is an agroecological-based philosophy, which uses consciously designed landscapes to mimic the diversity, stability, and resilience of natural ecosystems 2021. Through a sustainable integration between landscapes and people, *Permaculture* serves to fulfill human requirements for food, energy, shelter, and other material and non-material needs (Mollison, 1988).

NEF is 1.2 hectares in size, which is the average landholding size per family for smallholder farmers in Malawi (FAO, 2015). Despite the fact that Permaculture principles may be scaled up to design large-scale commercial farms or even urban cities (OSU and Millison, 2020), 1.2 hectares allows for the implementation of methods which are replicable in both size and scale for the majority of Malawians. In terms of soil management, NEF integrates a diverse range of methods, including: mulch, compost, green manure, liquid manure, agroecology, ecological succession, vermiculture, crop rotation, diversified polyculture, agroforestry, cover-crops, low-to-no till soil preparation, aquaculture, food forests, woodlot management, and intercropping. It has been estimated that in tropical climates it can take up to 200 years to form 1 cm of soil naturally (Osman, 2013). The methods employed by NEF, such as mulching with diversified organic matter up to 15-20 cm deep (often with multiple applications throughout the year in various areas), serves to promote the continual and regenerative return of organic matter, adding up to 2-4 cm of soil per year (the equivalent of 400-800 years of natural soil formation). NEF also places a significant emphasis on the designing of ecosystems which reflect the natural patterns and functionality of forest systems. Through the establishment of perennial tree crops, NEF is able to provide for year-round access to foods, medicines, fuel, building materials, fiber, shade, windbreaks, soil stabilization, and nutrient cycling.

3. Context of the case study

Malawi is a small country located in southeastern Africa. It has a population of just over 18 million, with about 11 million of those considered to be smallholder subsistence farmers. Malawi has a sub-tropical climate with a rainy season stretching from November-April, during which 95 % of the annual precipitation takes place. Central Malawi (the location of NEF) receives an average of 900 mm of rain per year, with temperatures ranging from 17-27 °C (cold season) to 25-37 °C (hot season) (MetMalawi, 2020). Soil in the area of NEF is generally ferruginous (red, clay soil).

4. Possibility of scaling up

NEF uses Permaculture principles to help Malawi meet the United Nations' Sustainable Development Goals, which are designed to help countries achieve social, economic, and environmental sustainability by 2030 (United Nations, 2018). The goals specific to NEF's work include: climate action, sustainable cities & communities, good health & wellbeing, zero hunger, responsible consumption & production, life on land, clean water & sanitation, no poverty, and partnerships for the goals. In addition, NEF conducts community outreach, hosts weekly tours, and runs an internship program to help train and certify community members in Permaculture Design. NEF has been influential in introducing *Permaculture* into national level programs through various development partners, such as the Ministry of Education's *School Health and Nutrition Program*, which piloted Permaculture implementation in eight districts in 40 primary schools, 10 teacher development centers, and one teacher training college. NEF has also been able to assist large-scale implementers, such as USAID, in helping to show how Permaculture can be used as a 'best practice' for development activities (Greenblott and Nordin, 2012).

5. Impact on soil organic carbon stocks

Specific soil analysis of any Permaculture site, and for NEF in specific, is difficult due to the fact that 10 different soil samples may yield 10 highly different results. The reason for this is that on any given site, the quantity and quality of organic matter, carbon levels, nutrients, soil structure/type, water retention, microbial activity, etc., may vary dramatically due to variations in microclimates, animal management, compost/mulching materials, soil biology (termites, worms, microorganisms, etc.), land usage, and the diversity of Permaculture practices being implemented. NEF has not conducted specific on-site carbon storage analysis, but the following chart gives estimations based on a few specific methods utilized by NEF as calculated by *Project Drawdown* (Table 8). The carbon sequestration rates calculated by Project Drawdown are based upon analysis of numerous data points from numerous sources. Duration also varies, for instance, the calculation for perennial staple crops assumes an orchard's duration to be 37.5 years, while other methods, such as silvopasture are perennial. Specifics on the methodology of analysis can be found on the technical summary for each solution evaluated (Drawdown, 2020).

Table 8. Estimation of the evolution of SOC stocks at NEF in Malawi

Method	Soil type	Additional C storage potential (tC/ha/yr)	Duration	More information	Reference
Multistratam agroforestry	Any	4.45	See technical summary (Draw-down, 2020)	NEF has established perennial food forests, which include multistrata agroforestry species	Draw-down (2020)
Perennial Staple Crops		3.34		NEF cultivates perennial staple crops such as local yams and air potatoes (*Dioscorea* spp.), cassava (*Manihot esculenta*), taro (*Colocasia esculenta*), and green bananas (*Musa* spp.)	
Silvopasture		2.74		NEF utilizes tree/forage designs with small animal husbandry, beekeeping, and aquaculture	

6. Other benefits of the practice

6.1. Improvement of soil properties

NEF aims to increase biodiversity, increase organic matter, and eliminate synthetic fertilizers and pesticides to enhance soil/plant/animal/insect/microorganism interactions. An analysis of these types of practices has shown that Permaculture soils were higher in nitrogen and bioavailable elements (e.g. calcium, magnesium, phosphorous, and potassium), as well as being higher in organic carbon and particulate organic matter, when compared to conventional plots (Tombeur *et al.*, 2018).

6.2 Minimization of threats to soil functions

Table 9. Soil threats

Soil threats	
Soil erosion	Malawi loses an average of 29 tons of soil per hectare per year (Worldbank, 2019). The regenerative Permaculture practices used at NEF (agroforestry, mulching, compost, perennial cover crops, etc.) reverse this trend, resulting in the regenerative creation and protection of new soil. The permanent bed system used by NEF can result in soil gains of up to 2-4 cm/year (Photo 6).
Nutrient imbalance and cycles	NEF focuses on overall nutrient cycling, including N,P,K. This is achieved through Permaculture practices such as: regenerative soil management (mulch, compost, perennial systems, etc.), swales, rainwater-catchment, bioremediation, and proper sewage/manure management.
Soil salinization and alkalinization	Chemical land degradation, including soil pollution and salinization/alkalization, has led to 15% loss in the arable land in Malawi in the last decade (Worldbank, 2019). Secondary salinization of soils, now affecting over 100 countries worldwide, is primarily caused by poor agricultural practices, including: inefficient cropping systems, inappropriate choices of crops, lack of crop rotation, poor tillage practices, and irrigation (Cuevas *et al.*, 2019). Permaculture methods used by NEF reverse these causes of secondary salinization and serve to increase the soil organic matter thereby making the soil more resistant to a rise or drop in pH levels (USDA, 2020); in addition, the formation of mycilial (fungal) networks in healthy soil has also been shown to aid in rendering salt inert (Kamel, 2013).
Soil contamination/ pollution	NEF uses organic, zero-waste, and agroecological principles to eliminate and remediate eventual soil contamination from synthetic chemicals (fertilizers, pesticides, herbicides) applied prior to NEF management. Fungi (Rhodes, 2014) and earthworms (Yadav, 2017) are used for both mycoremediation and bioremediation.
Soil acidification	Composting methods, such as those used by NEF, have been reported to end up with a pH level generally between 6 and 8 (Cornell, 1996). NEF also utilizes eco-san (composting toilets), which yields composted material with a slightly alkaline pH of around 7.4 (Jenkins, 2005).
Soil biodiversity loss	NEF uses multiple tools to enhance and conserve soil biodiversity including: compost, liquid manure, intercropping, perennial groundcovers, no-to-low till, mulch, intercropping, eco-san, vermiculture, and water harvesting.

Soil threats	
Soil sealing	NEF uses eco-friendly architectural methods, such as rammed earth and earth-bags (Nordin, 2018), along with water harvesting strategies on every structure.
Soil compaction	Mulching, agroforestry, and Permanent bed systems (in lieu of annual ridging) decompact the soil allowing for increased water absorption and storage. It also allows for 70 percent of cropland to be put under production as opposed to the current 50 percent (Nordin, 2019).
Soil water management	NEF has designed systems where every drop of rainwater is harvested into the soil, or into tanks for later use in the soil.

6.3 Increases in production (e.g. food/fuel/feed/timber)

In analysis conducted with community members neighboring NEF, it was found that those who were practicing Permaculture grew on average three times more crops overall, and more crop varieties per food group than conventional farmers, resulting in higher food security and diet diversity scores comparatively (Conrad, 2014). In terms of fuel, NEF took over land in 2003 that was devoid of trees. By 2006 NEF was supplying its own firewood needs and by 2016 there was such surplus from trimming that eight 50-kg bags of charcoal/biochar were made without destroying a single tree (Nordin, 2016).

6.4 Mitigation of and adaptation to climate change

In 2015-16, crop failure due to drought in Africa led to an estimated 50 million people needing food aid. 2016 was Southern Africa's driest seasons in 35 years. During this same period, NEF was able to grow over 200 different foods, including local yams weighing over 20 kg each (Vidal, 2016). The key to NEF's success lies in good soil and water management. Healthy soil acts like a sponge to absorb and hold water for greater periods of time. According to the USDA, for each 1% increase in organic matter, U.S. cropland could store the amount of water that flows over Niagara Falls in 150 days (USDA, 2017). During gaps in the rainfall, many Malawian farmers struggled with crop failure, with a reported 69% of farmers reporting maize (*Zea mays*) yields of less than 1 000 kg/hectare (Mungai, Messina and Snapp, 2020), which is 0.1 kg of maize per square meter. NEF soils (heavily mulched, intercropped, and protected by groundcovers) retained their moisture and produced good yields, resulting in a maize yields of 0.3 kg per square meter (or 3 300 kg/hectare). That total was only for maize and did not include additional yield values for harvests of pumpkins (*Cucurbita spp.*), beans (*Phaseolus spp.*), cassava, sweet potatoes, sunflowers (*Helianthus spp.*), and various green leafy vegetables.

6.5 Socio-economic benefits

Analysis of the NEF community indicated that *conventional* farmers (those relying primarily on the monocropping of maize through the purchase of inputs such as hybrid seeds, synthetic fertilizers, and chemicals) faced challenges given that the cost of conventional techniques did not improve their farm system in the long term. By contrast, *Permaculture* practitioners in the NEF community were able to use Permaculture education and practices to expand their skills, develop strategies to contend with constraints, and improvise responses to problems. Community members were able to use permaculture practices in a way that provided them with agricultural, environmental, and livelihood benefits (Conrad, 2014).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

No tradeoffs recorded.

7.2 Increases in greenhouse gas emissions

NA

7.3 Conflict with other practice(s)

Implementation of NEF design strategies are all based upon the three Permaculture ethics: *Earth Care*, *People Care*, and *Fair Share* (or a return of surplus) (Mollison, 1988). Therefore, these strategies would be in conflict with any practice, system, or science, which fails to adhere to these ethics.

7.4 Decreases in production (e.g. food/fuel/feed/timber/fibre)

Total output of a single crop, such as maize, would be lower at NEF when compared to a similar-sized monocropped system, but total system *yield* (harvests, surplus energy, add-on benefits) under Permaculture polyculture is higher when the diversity of production is added together—referred to as *additive yielding* (Jacke and Toensmeier, 2005). Malawi's national average for maize yield is 1 200 kg/ha (Mango *et al.*, 2018), which equates to 0.12 kg/m^2; by comparison, NEF has measured maize yields of 0.33 kg/m^2 (which, if scaled up would be 3 300 kg/ha, or 1 100 kg higher than the national average). Diversification is the key to maximizing yields; for instance, a single avocado (*Persea Americana*) tree at NEF is capable of yielding over 200 kg of food (KALRO, 2018), with the trunk of the tree using less than a single square meter of soil.

8. Recommendations before implementing the practice

It is recommended that practitioners of Permaculture complete a 72-hour design course. In Malawi, these courses are offered annually at various Permaculture training venues, as well as being an integral part of NEF's internship program. The course follows an international curriculum and covers topics such as: ethics, methods of design, ecosystems, patterns, land restoration, water management, soil rehabilitation, wildlife & animal management, appropriate technologies, food forests/guilds, and community development (Kusamala, 2020). There are also several introductory courses offered annually throughout the country (in English and local language), which do not result in an internationally recognized certificate, but do serve as a good starting point for implementation and future certification.

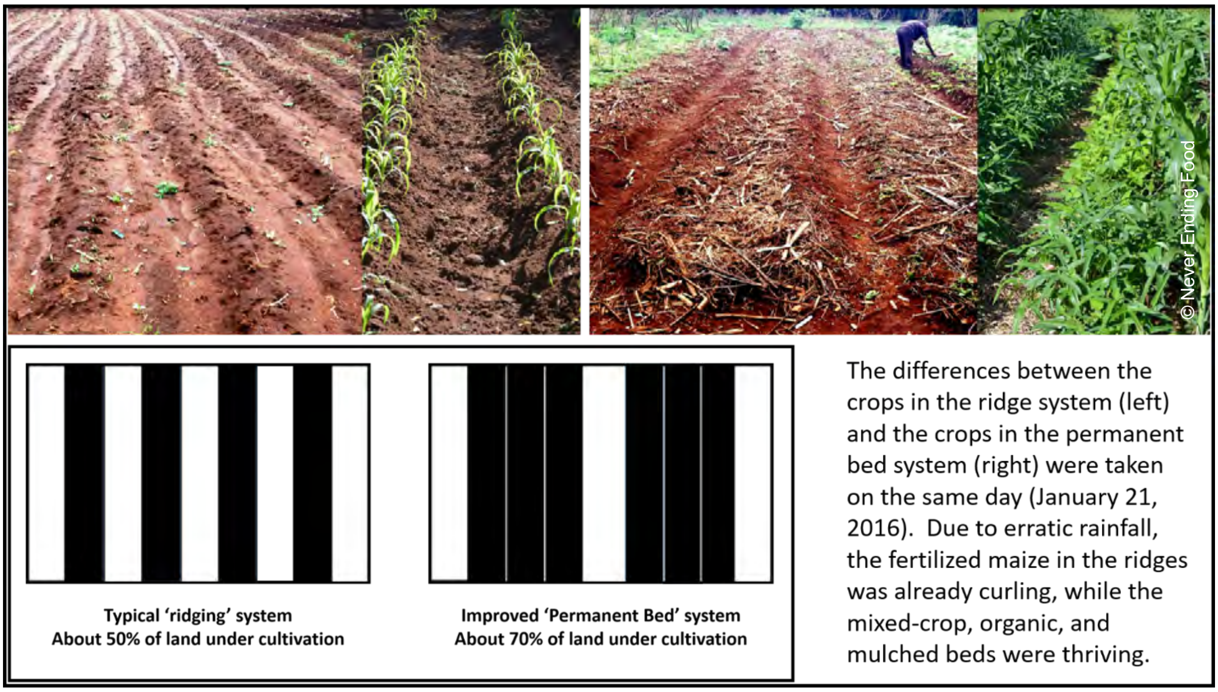
9. Potential barriers for adoption

Table 10. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Several Permaculture practices used by NEF are associated with cultural barriers. The use of mulching often contradicts health and conventional agriculture messages of sweeping and burning organic matter; there may be apprehension regarding the hygienic use of greywater and eco-san; and the establishment of forest systems can be associated with witchcraft in Malawi (Conrad, 2014).
Social	Yes/No	Analysis indicated that adoption of Permaculture practices, by community members in the area of NEF, was associated with age and land ownership but not with income or years of education. Gender roles, age, and social norms were also shown to create various challenges for the implementation of Permaculture practices (Thornton, 2008).
Economic	Yes/No	The fact that *Permaculture* is not dependent on access to money created options for NEF community members who learned about and used these methods, but financial access to land ownership has been associated higher adoption rates of *Permaculture* (Conrad, 2014).
Institutional	Yes	Within the NEF community, it was shown that the benefits of Permaculture are important where farmers face systemic risk to impoverishment, food insecurity, and malnutrition. However, the adoption of Permaculture was constrained by the broader agrofood system, resource entitlements, and other structural constraints (Conrad, 2014).

Barrier	YES/NO	
Legal (Right to soil)	Yes/No	Of the NEF community members interviewed by Thornton, all identified land ownership as a prerequisite to Permaculture, however, many in the study group were conducting Permaculture practices on rented land while few were fully utilizing the land they owned (Thornton, 2008).
Knowledge	Yes/No	Information and resources regarding Permaculture may be limited and sometimes contradictory to conventional agricultural messages (Conrad, 2014), however, of those who qualified as 'adopters' of Permaculture within the NEF community, 64% admitted to freely sharing knowledge (Thornton, 2008).

Photos



The differences between the crops in the ridge system (left) and the crops in the permanent bed system (right) were taken on the same day (January 21, 2016). Due to erratic rainfall, the fertilized maize in the ridges was already curling, while the mixed-crop, organic, and mulched beds were thriving.

Photo 6. The majority of Malawian farmers use a ridge-pathway-ridge system of farming where the ridges are split-and-turned each year

This means that ridges are turned and built upon the previous season's, leading to hard-panned soil, increased erosion, loss of soil fertility, reduced levels of carbon sequestration, and more vulnerability to the effects of floods and droughts. In 1998, it was reported that only 12% of these ridges were being built on contour (SDNP, 1998). By contrast, NEF uses a permanent one-meter bed system, which is mulched throughout the year with post-harvest crop residue and organic matter from agroforestry species. This reduces soil compaction, improves rainwater infiltration and absorption, increases the area available for cultivation by 20%, regenerates the soil by up to 2-4 cm/year, and allows for the intercropping of nitrogen-fixers and diversified nutrition (Nordin, 2019).

Photo 7. NEF's Permaculture Manager, Peter Kaniye, holding a local yam (Dioscorea spp.) which weighed 21.8 kg

Maize yields in Malawi have shown a steady decline where 61 percent (2010–11) and 69 percent (2016–17) reported yields as being less than 1000 kg/ha. A single yam can mature in soil space of 2 meters by 2 meters (4 m2). This means that 2 500 yams could be planted in a single hectare, and at 20 kg this could yield potential harvest rates of up to 50 000 kg/ha (or nearly 49 000 kg higher than the current national maize yields). This also does not take into account the fact that these yam vines like to climb trees, so cropping systems can be integrated with food-producing trees or agroforestry species, additional root and tuber crops, vegetables, legumes, grains, oil crops, and even small animal grazing—all pushing the total yields even higher.

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4. Conservation agriculture in Mozambique

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1. Related practices

Conservation agriculture, organic mulch, reduced tillage, legumes and cereals intercropping, adapted chemical fertilization.

2. Description of the case study

In Sub-Saharan Africa (SSA), the management of soil fertility is primordial for increased productivity and efficient use of the available resources. With declining land productivity, smallholder farmers in Southern Africa are shifting from conventional tillage to conservation agriculture (CA) as they realize that land management requires alternative actions to ensure sustainable productivity (Thierfelder *et al.* 2015; Thierfelder *et al.* 2018). This study aimed to identify the factors that influence smallholder farmers' decisions to adopt four different CA practices (i.e. minimum tillage, intercropping, cover cropping and crop rotation) in Mozambique. A non-probability sampling approach, incorporating both purposive and accidental sampling types, was followed. A questionnaire was administered to the 616 selected smallholder farmers. In addition, experiments were conducted to investigate the effects of tillage systems, (conservation and conventional tillage), two fertilization levels (fertilized and unfertilized) and seven cropping pattern (four sole cropping and three intercropping) on selected soil physical parameters (bulk density, penetration resistance, saturated hydraulic conductivity and evaporation) and soil chemical properties (pH, organic carbon, total nitrogen, extractable phosphorus, exchangeable cations, and cation exchange capacity) after two cropping seasons (2016/17 and 2017/18). The responses of the soil to fertilization were studied and a NPK (12:24:12) fertilizer mixture was applied at planting at 300 and 150 kg/ha for maize and legumes respectively. Top dressing with urea (46% N) at the recommended rate of 200 kg/ha was applied 35 days after planting only for maize. The study was carried out at Nhacoongo (24°19’49”S and 35°12’55”E), Mutuali (14°52’14.02”S 37°00’15.98”E), Lichinga (13°18’46.01”S and 35°14’26.02”E), and Gurúè (15°-19°09’05”S and 36^{0}42’43.9’’E) research experimental stations in Mozambique, four sites with different soil types and crop adaptation (Figure 2). Results from the survey revealed that household size, animal ownership, communication assets (such as television, radio, and cell phone) and group membership had a positive influence on CA adoption. Results from experiment revealed that CA practices increased bulk density (*Db*), penetration resistance (*PR*), and saturated hydraulic conductivity (*KS*) and decreased evaporation as compared to conventional tillage (CT). Enhanced organic carbon, total nitrogen, extractable phosphorus, soluble cations, exchangeable cations, and cation exchange capacity were recorded with the application of conservation agriculture practices compared with conventional tillage practices.

3. Context of the case study

This study was conducted at four research stations of the Agricultural Research Institute of Mozambique. These are, Nhacoongo in the Inhambane province in the southern region, Gurúè in the Zambézia province in the central region, Mutuali in the Nampula province and Lichinga in the Niassa province in the northern region of Mozambique (**Figure 2**). Some characteristics of the research station are given in **Table 11**. All sites receive unimodal rainfall between October and May ranging from 800 to 2 000 mm. Agricultural production is predominantly rainfed and with smallholder farmers relying on subsistence agriculture (MAE, 2005a, 2005b, 2005c, 2005d). The soils of Nhacoongo are loamy sands, Mutuali and Gurúè are sandy loams and Lichinga are sandy clay loams. In general, the highest gravel content was observed in Gurúè (5.00 percent) followed by Lichinga (3.28 percent), Mutuali (1.20 percent) and Nhacoongo (0.50 percent)

Table 11. Selected characteristics of the Nhacoongo, Lichinga, Gurúè and Mutuali research stations where the experiments were conducted

Location	Climate Zone	Province and disctrict	Annual Rainfall (mm)	Temperature (°C)	Altitude (M.A.S.L.)	Soil type*	Textural Class**
Nhacoongo	Tropical dry	Inhambane, Inharrime	1 000-1 200	18-33	68	Luvic Arenosols	Loamy sand
Mutuali	Tropical Moist	Nampula, Malema	800-1 300	15-36.6	574	Orthic Ferralsols	Sandy loam
Lichinga	Tropical Moist	Niassa, Lichinga	1 200-1 400	16.1-32.9	1 396	Orthic Ferralsols	Sandy clay loam
Gurue	Tropical Moist	Zambézia, Gurúè	1 800-2 000	15-23	678	Humic Nitisols	Sandy loam

Source: Adapted from MAE (2005a, 2005b, 2005c, 2005d), Maria and Yost (2006) and Gyogluu (2011)

*Based on FAO soil classification (FAO, 2016); **Based on USDA textural soil classification (USDA, 1987)

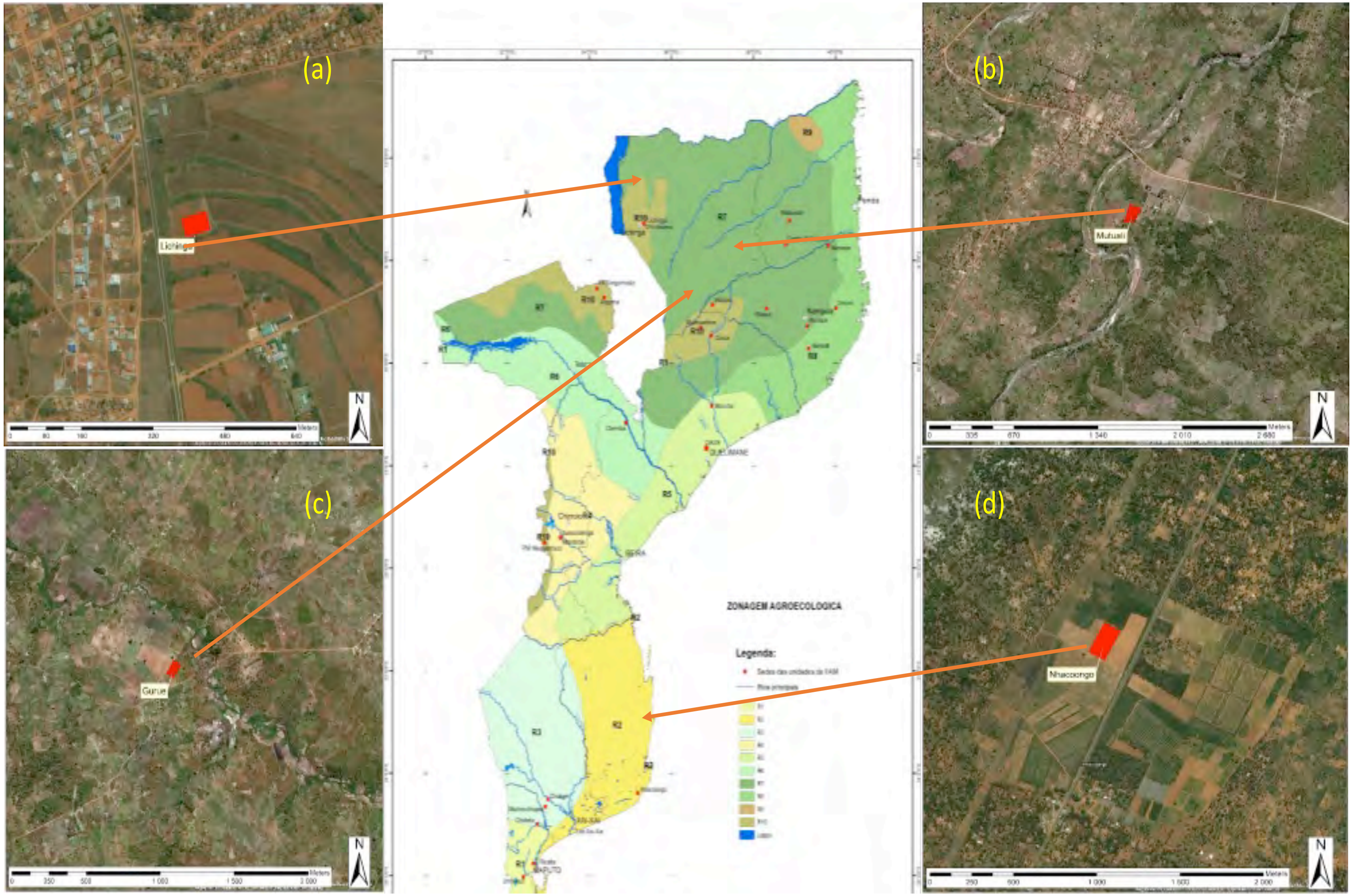

Figure 2. Locations of the Lichinga (a), Mutuali (b), Gurúè (c) and Nhacoongo (d) research stations in Mozambique where the study was conducted. Source: Oscar Chichongue

4. Possibility of scaling up

Between CT and CA practices, results from this study suggest that CA practices can be adopted by smallholder farmers as Shah and Wu (2019) and Li *et al.* (2020) indicated that reduced tillage can reduce water evaporation and improve soil chemical properties which can contribute to improved soil fertility status and enhanced crop yields. The use of fertilizers in short-term field experiments should be taken in consideration as an option to increase crop of inorganic yields and enhance adoption of CA practices. CA practices lead to sustainable improvement in efficient use of water and nutrients by improving nutrient balance and availability, infiltration and retention by the soil, decreasing water loss due to evaporation and improving availability of ground and surface water (Drechsel *et al.* 2015). CA practices reduce carbon emission by enhanced carbon sequestration by not destroying dead crop residues and increasing soil organic matter (Reicosky, 2008).

5. Impact on soil organic carbon stocks

The below table gives information on the C stock change over 2 years. Measurements have been made in the top layer (0-12 cm depth) of the soil. The experimental design was a randomized complete block design with a split-split plot arrangement, replicated four times at each experimental site. Two tillage systems were applied in the main plots (CA and CT), seven cropping pattern as the sub plots (one level of sole maize, three levels of sole legumes and three levels of maize-legume intercrop) and two levels of fertilization in the sub-sub plots (fertilized and unfertilized) totalizing 28 plots (14 plots under CA practices and 14 plots under CT practices) (Table 12).

The baseline C stock are values of organic carbon from CT and C stock from improved technology are values of organic carbon from CA practices and additional C storage is the difference between C stock in CA practices and C Stock in CT practices.

Table 12. Carbon storage for CT and CA at each experimental site

Location	Climate zone	Soil type	Baseline C stock in CT (tC/ha)	C stock in CA (tC/ha)	Additional C storage (tC/ha/yr)	More information	Reference
Nhacoongo	Tropical dry	Loamy sand	9.30	13.94	2.32	The baseline C represents organic carbon in CT and CA practices while Additional C storage represents organic carbon gained by improved practices	Experimental results from APPSA* funded sub-project conducted in Mozambique
Mutuali	Tropical Moist	Sandy loam	14.50	17.13	1.31		
Lichinga	Tropical Moist	Sandy clay loam	23.04	28.17	2.57		
Gurúè	Tropical Moist	Sandy loam	11.61	16.66	2.53		

*Agricultural Productivity Program for Southern Africa (APPSA) sub-project funded by the World Bank

The experiment in each study site consisted in 14 fertilized plots and 14 unfertilized plots (7 plots under CA*fertilized*cropping pattern; 7 plots under CA*unfertilized*cropping pattern; 7 plots under CT*fertilized*cropping pattern; and 7 plots under CT*unfertilized*cropping pattern) (Table 13).

Table 13. Carbon storage affected by fertilization at each experimental site at 0-12 cm depth

Sites	C stock (tC/ha)				C Storage (tC/ha)	
	CT*Fertilized	CA*Fertilized	CT*Unfertilized	CA*Unfertilized	Fertilized	Unfertilized
Nhacoongo	7.96	11.54	7.64	11.39	3.58	3.75
Mutuali	12.47	14.55	11.9	13.63	2.08	1.73
Lichinga	20.92	22.91	19.05	22.41	1.99	3.36
Gurue	9.87	14.07	9.77	13.55	4.2	3.78

6. Other benefits of the practice

6.1 Improvement of soil properties

Physical properties

The results revealed some significant differences related to the tillage system across the four experimental sites, indicating higher values of bulk density (*Db*), penetration resistance (*PR*), and Subgrade reaction *(Ks)* under CA system when compared to CT.

The *Db* was influenced by tillage system at Nhacoongo, Mutuali and Lichinga but not at Gurúè. At these sites, CA recorded a higher bulk *Db* (Nhacoongo=1.57, Mutuali=1.17, Lichinga=1.29 and Gurúè=1.06 g/cm^3) than under CT (Nhacoongo=1.55, Mutuali=1.14, Lichinga=1.20 and Gurúè=1.04 g/cm^3).

The effect of tillage system on *PR* was significant only at Nhacoongo and Gurúè. However, *PR* values across the four study sites were consistently higher under CA systems (ranging from 1.05 MPa to 2.70 MPa) compared to CT system (ranging from 0.55 to 2.40 MPa). Therefore, CA system offered more resistance to root development than CT.

The *Ks* was affected significantly ($P \leq 0.05$) by tillage system in Nhacoongo, Lichinga, and Gurúè but not in Mutuali. Generally, average *Ks* values were higher under CA systems (Nhacoongo=74.30, Mutuali=51.70, Lichinga=61.90 and Gurúè=66.90 cm/h) than under CT (Nhacoongo=64.80, Mutuali=45.40, Lichinga=37.40 and Gurúè=38.40 cm/h).

Evaporation at soil surface was higher in CT system than in CA system (Figure 3). The decline in evaporation under CA when compared to CT is a short-term benefit of CA that can have beneficial effects on yield and should be explored in future to optimize this in order to promote CA under smallholder farmers.

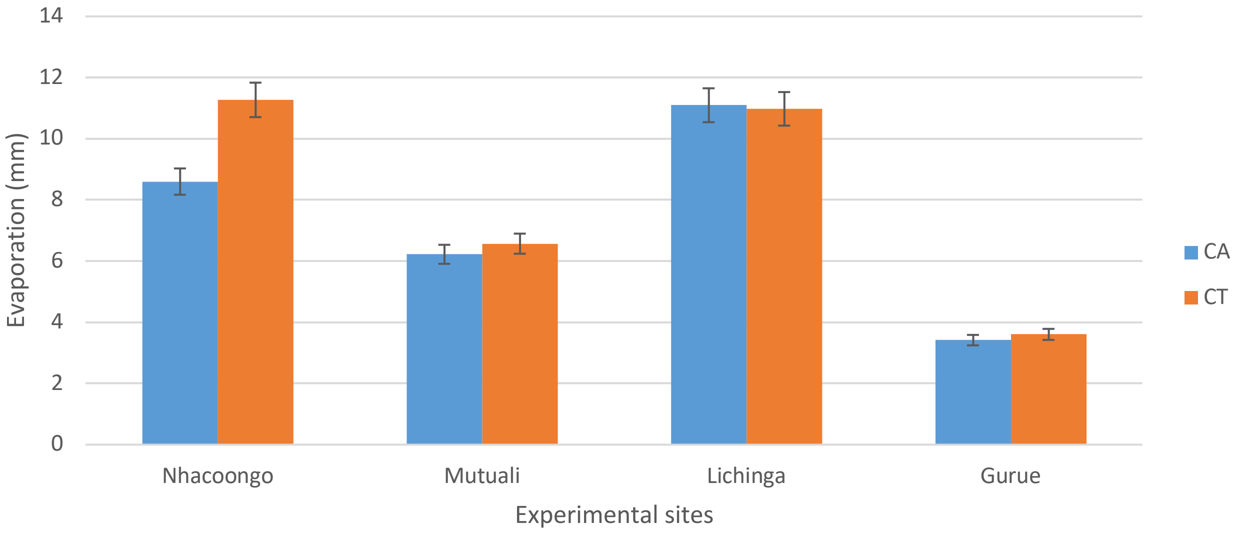

Figure 3. Evaporation at four experimental sites

Chemical properties

In this study, tillage systems had a significant effect on soil chemical properties (Table 14). After two years CA resulted in greater pH, organic C, total N, extractable P, extractable bases, and CEC compared to CT.

The *pH* was influenced by tillage system at all four sites (Nhacoongo, Mutuali and Lichinga and Gurúè). At these sites, CA recorded a higher *pH* (Nhacoongo=5.93, Mutuali=6.10, Lichinga=5.39 and Gurúè=6.41) than under CT (Nhacoongo=5.45, Mutuali=5.91, Lichinga=4.87 and Gurúè=6.23).

The *organic C* was affected significantly ($P \leq 0.05$) by tillage system at all four sites. Generally, average *organic C* values were higher under CA systems (Nhacoongo=0.74, Mutuali=1.22, Lichinga=1.82 and Gurúè=1.31 percent) than under CT (Nhacoongo=0.50, Mutuali=1.06, Lichinga=1.60 and Gurúè=0.93 percent).

The *Total N* was influenced significantly ($P \leq 0.05$) by tillage system at all four sites. *Total N* values across the four study sites were consistently higher under CA systems (ranging from 0.07 to 0.09 percent) compared to CT system (ranging from 0.05 to 0.08 percent).

The *extractable P* was influenced by tillage system at Nhacoongo, Mutuali and Gurúè but not at Lichinga. At these sites, CA recorded a higher *extractable P* (Nhacoongo=14.71, Mutuali=16.25, Lichinga=29.29 and Gurúè=59.59 mg/kg) than under CT (Nhacoongo=9.84, Mutuali=7.40, Lichinga=28.42 and Gurúè=47.35 mg/kg).

The *CEC* was affected significantly ($P \leq 0.05$) by tillage system at Nhacoongo, Lichinga and Gurúè but not at Mutuali. The *CEC* values across the four study sites were consistently higher under CA systems (ranging from 5.94 to 8.45 cmol/kg) compared to CT system (ranging from 3.25 to 9.05 cmol/kg).

Fertilization and cropping pattern had, in most cases, no significant influence on soil chemical proprieties (Table 14). The interaction between tillage systems and fertilization and tillage systems and cropping pattern in most cases showed significant differences in soil chemical properties while the interaction between fertilization and cropping pattern as well as the interaction of tillage systems, fertilization and cropping pattern were found to have no significant differences in most cases for soil chemical properties (pH, organic carbon, total nitrogen, extractable phosphorus, exchangeable cations, and cation exchange capacity).

Table 14. Effect of tillage practices on selected soil chemical properties

Locations	Treatment	pH	C (%)	N %	C: N Ratio	P (mg kg^{-1})	Exchangeable cations (cmol kg^{-1})				CEC (cmol kg^{-1})
							Ca	Mg	Na	K	
Nhacoongo	CA	5.93 a	0.74 a	0.08 a	9.13 a	14.71 a	1.76 a	0.83 a	0.27 b	0.29 a	5.94 a
	CT	5.45 b	0.50 b	0.05 b	10.27 a	9.84 b	1.06 b	0.46 b	0.37 a	0.25 b	3.25 b
	LSD	0.07	0.06	0.01	1.16	2.71	0.14	0.05	0.03	0.03	0.57
	Fertilization	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
	CP	ns	ns	*	ns	ns	ns	ns	ns	ns	ns
	CV (%)	3.27	23.57	22.28	31.86	58.74	25.5	21.22	26.64	33.08	32.95
Mutuali	CA	6.10 a	1.22 a	0.07 a	17.41 a	16.25 a	8.66 a	2.00 a	0.43 a	1.58 a	8.45 a
	CT	5.91 b	1.06 b	0.07 a	15.02 b	7.11 b	7.15 b	1.57 b	0.35 b	1.54 a	8.83 a
	LSD	0.1	0.08	0.01	1.31	2.18	1.05	0.23	0.06	0.14	0.95
	Fertilization	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	CP	ns	ns	ns	ns	ns	*	*	ns	ns	ns
	CV (%)	4.39	18.11	21.84	21.56	49.72	35.21	33.81	44.02	23.08	29.14
Lichinga	CA	5.39 a	1.82 a	0.09 a	22.53 a	29.29 a	3.40 a	2.18 a	0.88 a	1.03 a	7.48 a
	CT	4.87 b	1.60 b	0.08 b	22.16 a	28.42 a	2.80 b	1.11 b	0.47 b	0.61 b	6.07 b
	LSD	0.09	0.13	0.01	3.19	2.36	0.31	0.23	0.21	0.08	0.51
	Fertilization	ns	ns	ns	ns	*	*	*	ns	*	ns
	CP	ns	ns	ns	ns	ns	*	ns	ns	*	ns
	CV (%)	4.87	19.8	24.14	37.96	21.77	26.42	37.19	81.16	26.36	21.17
Gurue	CA	6.41 a	1.31 a	0.07 a	20.06 a	59.59 a	7.24 a	1.65 a	0.20 a	1.61 a	7.87 b
	CT	6.23 b	0.93 b	0.05 b	18.38 a	47.35 b	7.66 a	1.05 b	0.11 b	1.04 b	9.05 a
	LSD	0.11	0.09	0.004	1.1	5.36	0.91	0.14	0.06	0.15	0.78
	Fertilization	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	CP	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	CV (%)	4.64	22.2	16.03	23.58	26.66	32.64	27.02	98.15	30.39	25.52

Source: Chichongue (2020)

CA, conservation agriculture; CT, conventional tillage; CP, cropping patterns; ns, not significant; *, Significant at $p \leq 0.05$; CEC, cation exchange capacity; Means followed by different letters within a column are significantly different using Tukey's test at $p \leq 0.05$.

6.2 Minimization of threats to soil functions

Table 15. Soil threats

Soil threats	
Nutrient imbalance and cycles	Crop residue, intercropping and fertilization - increased and stabilized soil properties such as total nitrogen, cation exchange capacity and organic carbon accumulation leading to improved soil fertility.
Soil contamination / pollution	Soil Cover - Less herbicide use after CA practices are consolidated
Soil compaction	Bulk density and penetration resistance - CA practices decrease soil compaction leading to increased soil aeration and water uptake observed by lower bulk density and penetration resistance. Whereas results from this study showed that CA system increased Db resulting in increased compaction and less aeration compared to the CT system. Furthermore, CA system offered more resistance to root development than CT system. This can be attributed to the short study period (two cropping cycles) that could not improve physical soil properties;
Soil water management	Saturated hydraulic conductivity and evaporation - Crop residues or cover crops reduces the loss of water by covering at least 30% of the soil surface. Across the four study site water retention was increased and evaporation at soil surface was higher in CT system than in CA system. CA practices reduced evaporation.

6.3 Increases in production (e.g. food/fuel/feed/timber)

Maize (*Zea mays*) is a major staple food and cash crop for smallholder farmers in Mozambique. It is annually grown on about 85 percent of the cropped area under rainfed conditions. Yields remain very low and are estimated in most cases. Over the past 20 years, the average maize yield in Mozambique is very low and estimated to be less than one tonne (t) per hectare (ha) (Mango *et al.,* 2018; FAOSTAT, 2020[1]). Those yields are low compared to 1.7 t/ha in Malawi and 3.8 t/ha in South Africa[1] (FAOSTAT, 2020). In our study, tillage system significantly affected stover yield except for Mutuali as well as for Gurúè in the first cropping season and Lichinga in the second cropping season and ranging from 1.02 to 3.80 t/ha. At all four sites a greater stover yield was recorded under CA system than under CT system except in Gurúè in first cropping season where the CT system resulted in a higher stover yield than the CA system. Fertilization alone showed significant effects on

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[1] Calculated average yield between 1998 and 2018.

stover yield with higher values being recorded for fertilized plots ranging from 1.27 to 3.74 t/ha compared to unfertilized plots ranging from 1.05 to 2.79 t/ha. The presence of legumes in an intercropping system with maize generally improved stover yield as compared to any sole crop system. Furthermore, sole legume cultivation resulted in very low stover yield.

Tillage system, fertilization and cropping pattern significantly affected grain yield at all sites in both cropping seasons except for tillage system in Nhacoongo in the second cropping season (2018). The CA plots produced higher grain yields ranging from 1.32 to 2.95 t/ha compared to CT varying from 0.81 to 2.13 t/ha. The grain yield in the second cropping season was found to be generally greater as compared to the first cropping season. Fertilized plots produced a higher maize grain yield varying from 1.25 to 2.69 t/ha compared with unfertilized treatments plots, varying from 0.87 to 2.07 t/ha. The greater grain yield under CA might associated with better grain weight as a result of the conditions with this tillage, e.g. less runoff, increased soil water content leading to improved water holding capacity and lower evaporation. Fertilized treatments improved the maize and legume growth and accumulated more dry matter and greater grain yields. This indicated that fertilization played a critical role in determining the actual grain yield and clearly emphasized the sensitivity of maize to fertilization (Figure 4).

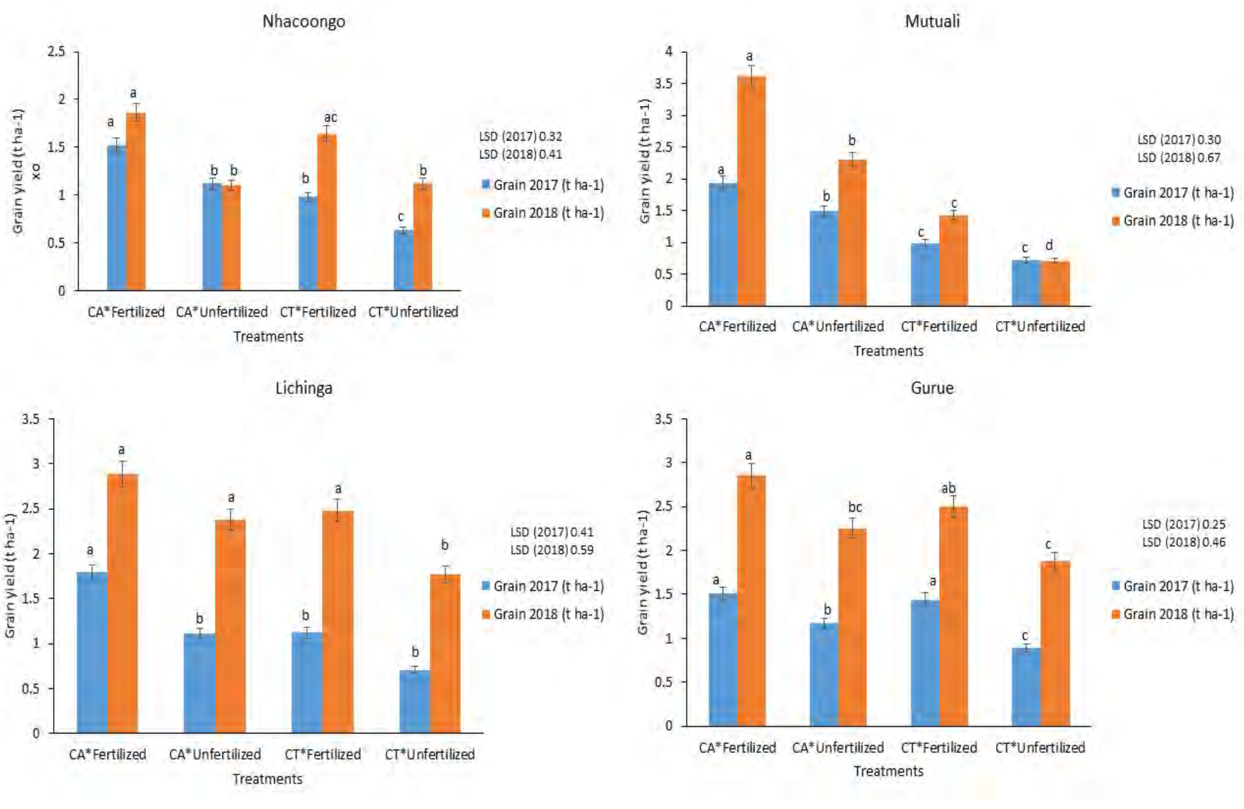

Figure 4. Grain yield at experimental sites

6.4 Mitigation of and adaptation to climate change

Although no GHG measurements were made at the time of the study, it is known that CA practices contribute to climate change mitigation through reduction in source and increase in sink carbon (Lal, 1997; Lenka and Lenka, 2014). CA practices contribute to increased soil C sequestration by increasing C sink capacity, leading to climate change mitigation. CA practices have the potential to increase organic carbon pool by capturing C inputs and decreasing C loss due to intensive ploughing (conventional tillage) thus reducing agriculture' potential for global warming. A study done by Lal (2003) and Busari *et al.* (2015) confirmed that conservation tillage has been associated with potential climate change mitigation C storage.

6.5 Socio-economic benefits

Direct benefits of CA practices to smallholder farmers are reduced cost of cultivation through savings in labor, reduce number of trips required for farming operation. It also reduces water usage and fertilization requirement under certain conditions. For example, inclusion of legumes in the cropping systems can significantly improve nutrient balances in soils, especially with regards to biological nitrogen fixation resulting in decreased N fertilizer demand. Cover crops and dead crop residues ensure effective weed control leading to reduced labor requirement. The CA practices increases habitat for wildlife (e.g. ground-nesting birds).

7. Conflict with other practices

These operations include ploughing to produce a seedbed and also is characterized by field removal of crop residue or burned in the field, leaving the field with less than 15 percent of soil cover, and high labor requirement (Barut and Akbolat, 2005) leading to degradation of soil physical and chemical characteristics (e.g. reduction of the levels of organic matter). To overcome all those constraints CA practices was suggested as an option that smallholder farmers can apply to improve soil fertility and improve the soil's productivity (Thierfelder *et al.* 2013). However, the adoption rate among smallholder farmers is still very low and usually, only some of the CA principles are adopted. Improved soil fertility achieved after the consolidation of CA practices, may allow overtime, decreases in fertilizer use, which will contribute to reduce the production costs and also reduce the environmental impact of the activities.

8. Recommendations before implementing the practice

The adoption study showed that most smallholder farmers did not adopt all components of CA practices. Results obtained revealed that household size, education, labor demand, occupation, animal ownership, communication assets (such as television, radio, and cell phone), group membership, farm size, land tenure and training had a positive influence on CA adoption while gender of the household head, perception on soil fertilty and on climate change was negatively related to CA adoption. Interestingly, female-headed households, more educated (formal and informal), and household size with more than 5 members were more likely to adopt CA practices. To increase adoption of CA practices these factors should be incorporated in the design of policies and strategies.

9. Potential barriers for adoption

Table 16. Potential barriers to adoption

Barrier	YES/NO	Results from study survey done in Mozambique (Chichongue *et al.* 2019)
Biophysical	Yes	**Fertility and Erosion:** Household farmers´ perception about a decline in soil fertility and deterioration of soil due to erosion decreased the chance of adoption of CA practices. This could be explained by the fact that farmers were not able to recognize the problem and were not aware of how CA practices mitigated those problems. **Climate change:** The perception of rainfall changing patterns and extreme temperature, negatively and significantly influenced the adoption of CA practices. **Farm size:** This variable have a positive and significant influence on the adoption of CA practices. Farmers who own larger farms can allocate some part of their land to try improved technologies, such as CA practices, and distribute associated risks.
Social	Yes	**Age and Experience :** The farming experience and age of a smallholder farmer can enhance or diminish the adoption of new technology. Age had negative effects as older farmers had shorter planning horizons and were less likely to invest in long-term CA practices than younger farmers. More experienced farmers mean they gained knowledge working in a variable production environment, which can contribute to their adoption decision. **Gender :** In SSA household heads are usually the main decision-makers who decide on the adoption of improved technologies. Male-headed households in general have a higher probability for the adoption of improved technologies whereas this study found that female-headed households were significantly more likely to adopt CA practices than their male counterparts. **Household size and labor demand**: In most countries in SSA, farmers rely on family labor for crop production. Household size is therefore associated with the availability of labor for farm operations. A larger household was expected to have a positive effect on adoption compared to smaller households; Household farmers who were not able to hire external labor were less likely to CA practices. **Education:** Smallholder farmers' formal and informal education (short- and long-term training) improves the farmers' management capacity and understanding of the benefits and constraints of CA practices and plays a social role, which significantly and positively influences the adoption of CA practices;

Barrier	YES/NO	Results from study survey done in Mozambique (Chichongue *et al.* 2019)
		Communication assets: Mass media ownership such as radio, television and mobile phones were found to have a significant and positive effect on the adoption of CA practices.
Economic	Yes	**Profitability (Income):** The smallholder's capacity to generate income for the household can have a positive or negative effect on the adoption of CA practices. Adoption of improved technologies increases as net farm income to household farm operators' increases whereas high net farm returns household farmers are less likely to invest in long-term practices (CA practices) as it may be enough to maintain food security of the household.
Institutional	Yes	**Land tenure:** Land tenure security was significant and positively affected the adoption of CA practices. Household farmers who were land insecure were more likely to practice CA practices, while land secure farmers were more encouraged to use long-term practices; **Access to extension services:** Household farmers who did not receive regular visits from extension agents or did not participate in field days or demonstrations, had a lower probability of adoption than those who were exposed to such activities.

Photos


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Photo 8. Minimum tillage


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Photo 9. Dead soil cover

Photo 10. Crop association (Cereal-legume intercropping)

Photo 10. Crop rotation

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5. Conservation agriculture in South Africa

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1. Related practices

Conservation agriculture, Reduced tillage, Intercropping, Crop rotations, Mineral fertilization

2. Description of the case study

The Zeekoegat trial was initiated in November 2007 and continued for six cropping seasons. A split plot randomized complete block design was used, with three replicates. Each replicate was split into two tillage systems, conventional tillage (CT) and reduced tillage (RT) and then further subdivided into twelve treatments (six cropping systems × two fertilizer levels), resulting in a total of 72 experimental plots. Plot dimensions were 7.2 m x 8.0 m. The cropping systems tested included: maize monoculture, maize/cowpea rotation, maize/soybean rotation (MSR), maize/cowpea intercropping, maize/oats intercropping and maize/vetch intercropping (Table 17). Details of activities are summarized in Table 18.

Table 17. Cropping rotation

Year	Maize monoculture	Maize/cowpea rotation	Maize / soybean rotation	Maize/ cowpea intercropping	Maize/oats delayed intercropping	Maize/ grazing vetch delayed intercropping
1	Maize full stand	Cowpea full stand	Soybean full stand	Maize full stand Soybean half stand	Maize full stand Oats 50 kg/ha	Maize full stand Vetch 30 kg/ha
2	Maize full stand	Maize full stand	Maize full stand	Maize half stand Soybean 3/4 stand	Maize half stand Oats 50 kg/ha	Maize half stand Vetch 30 kg/ha
3	Maize full stand	Cowpea full stand	Soybean full stand	Maize half stand Soybean 3/4 stand	Maize half stand Oats 50 kg/ha	Maize half stand Vetch 30 kg/ha
4	Maize full stand	Maize full stand	Maize full stand	Maize half stand Soybean 3/4 stand	Maize half stand Oats 50 kg/ha	Maize half stand Vetch 30 kg/ha
5	Maize full stand	Cowpea full stand	Soybean full stand	Maize half stand Soybean 3/4 stand	Maize half stand Oats 50 kg/ha	Maize half stand Vetch 30 kg/ha
6	Maize full stand	Maize full stand	Maize full stand	Maize half stand Soybean 3/4 stand	Maize half stand Oats 50 kg/ha	Maize half stand Vetch 30 kg/ha

This (for fertilizer levels) and two tillage systems (RT = reduced tillage and CT = conventional tillage, cowp = cowpea, soy = soybean)

Table 18. Details of farming activities at Zeekoegat trial for each season

	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13
Conventional tillage (300 mm deep)	Mouldboard plough	Slasher/ Mouldboard plough/disk harrow	Slasher/Mouldboard plough/four tine cultivator frame	Slasher/Mouldboard plough/four tine cultivator frame	Slasher/Mouldboard plough/four tine cultivator frame	Slasher/Mouldboard plough/four tine cultivator frame
Reduced tillage (200 mm deep)	Slasher/Hand hoes	Slasher/Hand hoes	Slasher/four tine cultivator frame	Slasher/four tine cultivator frame	Slasher/four tine cultivator frame	Slasher/four tine cultivator frame
Fertilizer, maize (optimal)* (kg/ha)	N=48+24*** P=13+7 K=12	N=46+21 P=20+2 K=0 **	N=42+28 P=13+2 K=0	N=42+28 P=13+2 K=0	N=42+30 P=8+5 K=0	N=42+30 P=6+6 K=0
Fertilizer, legumes (optimal) (kg/ha)	N=0 P=5 K=12	N=0 P=26 K=0	N=0 P=11 K=0	N=0 P=8 K=0	N=0 P=9 K=0	N=0 P=8 K=0
Fertilizer, oats (optimal) (kg/ha)	N=28 P=13 K=8	N=46 P=20 K=0	N=42 P=13 K=0	N=42 P=13 K=0	N=42 P=13 K=0	N=42 P=6 K=0
Target densities	Maize full stand: 37 000 plants/ha Maize intercrop: 37 000 plants/ha Legume full stand:	Maize full stands: 37 000 plants/ha Maize intercrop: 18500 plants/ha	Maize full stands: 37 000 plants/ha Maize + intercrop: 18 500 plants/ha	Maize full stand: 37 000 plants/ha Maize + intercrop: 18 500 plants/ha	Maize full stand: 37 000 plants/ha Maize + intercrop: 18 500 plants/ha	Maize full stand: 37 000 plants/ha Maize + intercrop: 18 500 plants/ha

	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13
	60 000 plants/ha Legume intercrop: 30 000 plants/ha Oats: 50 kg seed/ha Vetch: 30 kg seed/ha	Legume intercrop: 30 000/ha Oats: 50 kg seed/ha Vetch: 30 kg seed/ha	Legume: 150 000 plants/ha Intercrop: 100 000 plants/ha Oats: 50 kg seed/ha Vetch: 30 kg seed/ha	Intercrop: 100 000 plants/ha Oats: 50 kg seed/ha Vetch: 30 kg seed/ha	Legume: 150 000 plants/ha Intercrop: 100 000 plants/ha Oats: 50 kg seed/ha Vetch: 30 kg seed/ha	Intercrop: 100 000 plants/ha Oats: 50 kg seed/ha Vetch: 30 kg seed/ha
Planting date	Maize: 27/11/2007 Legume: 27/11/2007 Intercrop: 17/12/2007 Oats, vetch: 26/02/2008	Maize: 17/11/2008 Intercrop: 17/12/2008 Oats, vetch: 25/02/2009	Maize: 19/11/2009 Legume: 19/11/2009 Intercrop: 17/12/2009 Oats, vetch: 7/03/2010	Maize: 29/11/2010 Intercrop: 21/12/2010 Oats, vetch: 18/03/2011	Maize: 29/11/2011 Legume: 29/11/2011 Intercrop: 19/12/2011 Oats, vetch: 13/03/2012	Maize: 19/11/2012 Intercrop: 12/12/2012 Oats, vetch: 24/04/2013
Herbicide and pesticide (before planting + follow-up)	Roundup/Dual gold/ Cyperin + manual weeding	Roundup/Dual gold/ Cyperin + manual weeding	Roundup/Springbok/ Dual Gold/Cyperin + manual weeding	Roundup/Dual Gold/ Cyperin + manual weeding	Cleanup/Cypermetrial/ Dual Gold/ Cypermetian + manual weeding	Cleanup/ Cypermetrian/Dual Gold + manual weeding
Cultivar maize	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110	Pannar 6P/110
Cultivar cowpea	Mixed variety	Mixed variety	Mixed variety	Mixed variety	Mixed variety	Mixed variety
Cultivar soybean	Glenda	Glenda	Glenda	Glenda	Glenda	Glenda
Cultivar oats	SSH 491	SSH 491	SSH 491	SSH 491	SSH 491	SSH 491

*Fertilizer application for 'Low' treatments, were 50% of that reported for optimal

**From the second year, no K was applied, due to the high natural K content in the soil

***'+' indicates splitting of fertilizer: at planting + top-up

3. Context of the case study

Zeekoegat (25°36'55"S, 28°18'56" E, altitude: 1168 m) was an on-station trial at Zeekoegat experimental farm situated in Gauteng province, South Africa. The experimental trial was site-specific and has a footprint of 70 m x 20 m. This is located in the warm temperate, winter dry, hot summer region (Cwa). The site received an annual rainfall of 871 mm/yr (average of 6 trial years) with average maximum annual temperature of 27°C and minimum temperature of 10.7 °C. The soil at Zeekoegat is a Rhodic Nitisol (IUSS, 2014) with clayey (44.5% clay) texture, red, moderately fine to medium blocky structure on underlying gabbro. The soil is deep (>120 cm) and well drained with manganese concretions at deeper levels of 7% and 23% in the A and B horizons, respectively (Mampana *et al.*, 2015). The soil was slightly acidic and had relative low topsoil P content. Table 19 summarizes selected soil physical and chemical properties of the two sites at the start of the trials.

Table 19. Initial top-soil properties of Zeekoegat

Soil Depth (mm)	Soil texture (% clay)	Bulk density (t/m3)	pH (H2O)	SOC (g/kg)	P (Bray-I)(mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)
0-100	Clay (44%)	1.4	6.1	12.5	5	485	1189	265
100-300	Clay (45%)	1.4	5.9	12.4	4	536	1219	272

4. Possibility of scaling up

Site-specific CA practices used were line with local soil and climate conditions. Our research captured all supporting information available, such as management practices, biophysical properties etc., so that we can determine the underlying factors that is responsible for the observed changes. Using these driving forces and mechanisms, we can upscale our results to other regions with different climate or soils.

5. Impact on soil organic carbon stocks

Carbon content has been measured for six consecutive years to monitor the change in SOC under different treatments. In this trial, SOC was build up in the soil under selected CA practices, such as RT and vetch intercropping systems, especially in the topsoil (

Figure 5). In Table 20, only the values of SOC stocks at the start and end of the trial are presented for the main treatment effect (tillage). The first year represent the initial SOC content, and the last year represent the effect of CA and conventional farming practices after six years. There are, however, more detailed information for different treatments (cropping systems and fertilizer levels) measured yearly (6 years) at separate soil layers (4 soil layers) (Swanepoel *et al.*, 2014; Swanepoel, 2018; Table 21). The effect of fertilizer rates and cropping systems on SOC was however, not significant (Figure 6 and Table 20). We measured SOC in concentration (%), and to convert concentration SOC to carbon stock in ton per hectare, we first calculated the soil volume in each layer for one hectare (100 m x 100 m); this volume is multiplied with bulk density to calculate the mass of soil for each layer; the mass of soil was then multiplied with the concentration of C in that layer to get the mass of C or C stock for each layer per hectare (Table 20).

Table 20. Outline of calculation for C storage (per hectare) in the first year of the trial

Year	Tillage	Soil depth	Bulk density	Volume soil	Mass of soil	Organic C	C storage
2006		cm	ton/m^3	m^3/ha	ton/ha	%	tC/ha
	CT	0-10	1.467	1000	1467	1.209	17.740
	CT	10-30	1.435	2000	2870	1.202	34.486
	CT	30-60	1.338	3000	4014	1.040	41.758
	Total C for 0-60 cm for CT in the first year						*93.984*
	RT	0-10	1.467	1000	1467	1.287	18.885
	RT	10-30	1.435	2000	2870	1.271	36.468
	RT	30-60	1.338	3000	4014	1.019	40.903
	Total C for 0-60 cm for RT in the first year						*96.255*
2013	CT	0-10	1.467	1000	1467	1.274	18.690
	CT	10-30	1.435	2000	2870	1.216	34.894
	CT	30-60	1.338	3000	4014	1.089	43.716
	Total C for 0-60 cm for CT after 6 seasons						*97.300*
	RT	0-10	1.467	1000	1467	1.419	20.809
	RT	10-30	1.435	2000	2870	1.245	35.737
	RT	30-60	1.338	3000	4014	1.091	43.773
	Total C for 0-60 cm for RT after 6 seasons						*100.319*

Compared to the last year of the trial, with specific reference to reduced tillage vs conventional tillage.

Source: Swanepoel et al. (2013); Swanepoel et al., (2018)

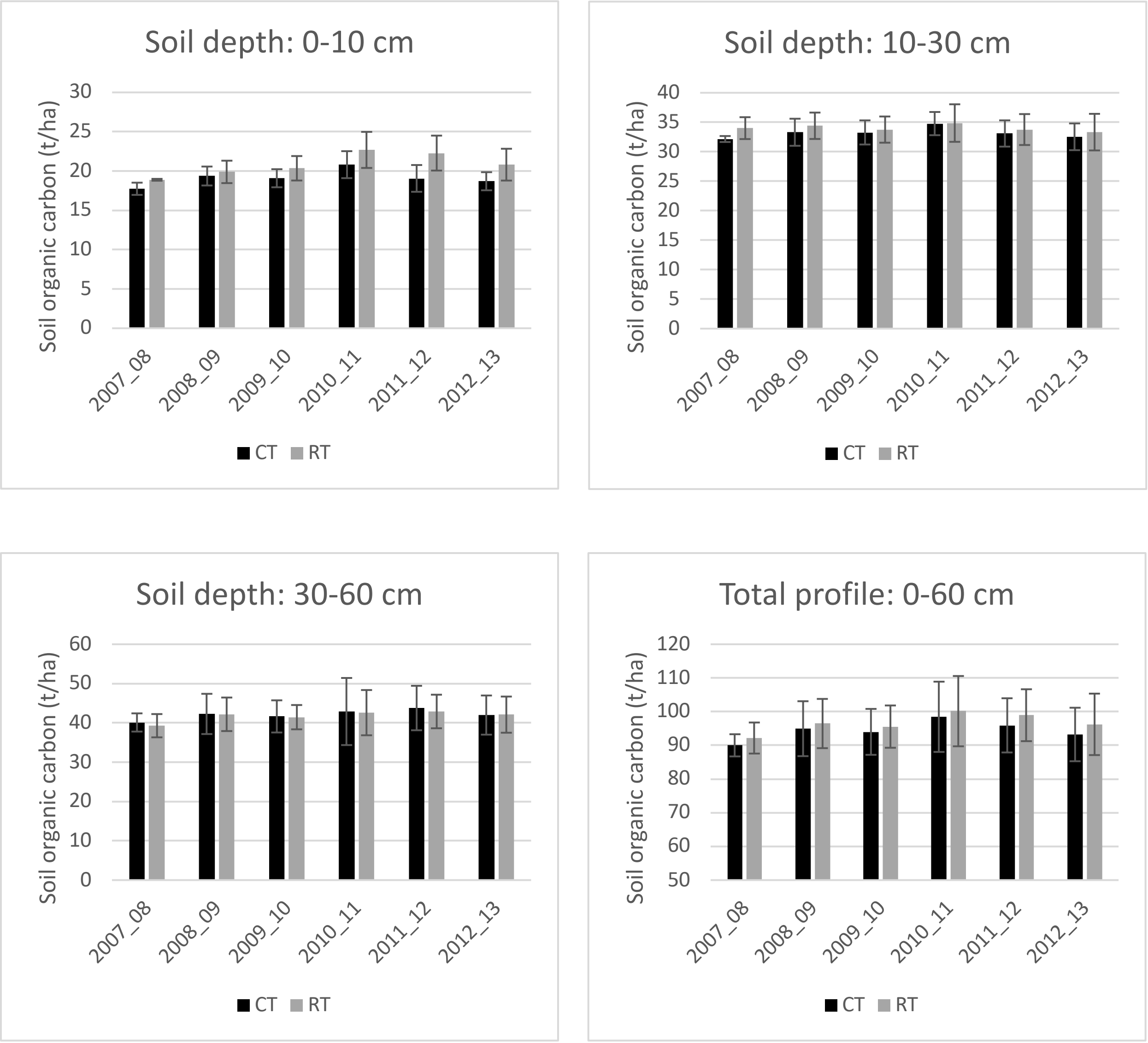

Figure 5. Summary of soil organic carbon stock (ton/hectare) in different soil depths as influenced by the main treatment effect, conventional tillage (CT) and reduced tillage (RT) (Swanepoel *et al.*, 2018)

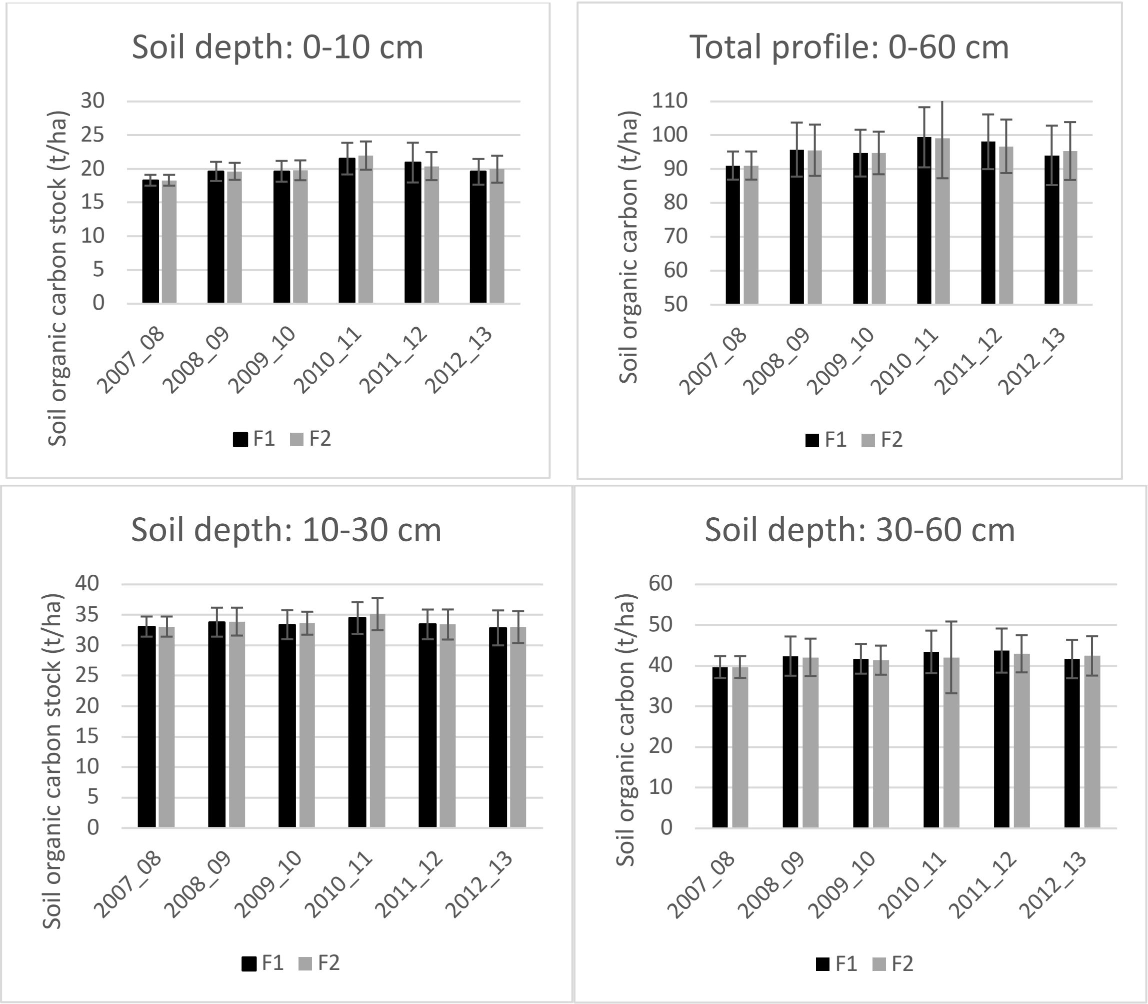

Figure 6. Comparing the effect of fertilizer (F1=half of optimal fertilizer; F2= optimal fertilizer application) on organic carbon stock (tC/ha) per year in three soil depths

Table 21. Average soil organic carbon stock (t/ha) as affected by cropping systems for each layer

Year	Cropping system	0-10 cm	10-30 cm	30-60 cm
2007-08	Original SOC stock	18.31	33.08	39.69
2008-09	1. Maize monocropping	19.53	34.19	42.18
	2. Maize - cowpea rotation	20.09	34.54	43.47
	3. Maize - soybean intercrop	19.21	32.62	41.51
	4. Maize - cowpea intercrop	19.60	33.99	42.44
	5. Maize – oats intercrop	19.55	33.90	42.82

Year	Cropping system	0-10 cm	10-30 cm	30-60 cm
	6. Maize – grazing vetch intercrop	19.77	33.87	40.96
2009-10	1. Maize monocropping	19.82	33.03	41.41
	2. Maize - cowpea rotation	19.92	34.32	42.95
	3. Maize - soybean intercrop	18.86	32.47	40.77
	4. Maize - cowpea intercrop	19.87	33.45	41.18
	5. Maize – oats intercrop	19.96	34.23	41.47
	6. Maize – grazing vetch intercrop	19.87	33.58	41.51
2010-11	1. Maize monocropping	21.99	34.63	43.56
	2. Maize - cowpea rotation	22.30	36.08	41.57
	3. Maize - soybean intercrop	19.99	33.58	42.34
	4. Maize - cowpea intercrop	21.90	34.61	42.50
	5. Maize – oats intercrop	22.24	35.48	43.72
	6. Maize – grazing vetch intercrop	22.05	34.52	42.76
2011-12	1. Maize monocropping	21.22	33.25	43.05
	2. Maize - cowpea rotation	20.37	33.85	43.91
	3. Maize - soybean intercrop	19.31	32.51	42.63
	4. Maize - cowpea intercrop	20.93	33.74	42.98
	5. Maize – oats intercrop	20.68	33.54	42.37
	6. Maize – grazing vetch intercrop	21.50	33.67	45.07
2012-13	1. Maize monocropping	20.10	33.12	42.69
	2. Maize - cowpea rotation	19.78	33.16	43.63
	3. Maize - soybean intercrop	18.59	31.49	40.73
	4. Maize - cowpea intercrop	19.80	33.23	41.73
	5. Maize – oats intercrop	19.71	33.41	42.53
	6. Maize – grazing vetch intercrop	20.55	33.18	40.93

6. Other benefits of the practice

6.1. Improvement of soil properties

Tillage systems were responsible for some differences in results, including the following:

- Soil nutrient dynamics: A gradual build-up of organic C was observed under RT in the topsoil (
-
-
- **Figure 5**). Tillage as a treatment also had an effect on K, Mg, NO_3 and total C, but the trend was not clear over time (Swanepoel *et al.* 2013).
- Aggregate stability: A positive correlation was drawn between aggregate volumes and aggregate stability and RT (Beukes and Swanepoel, 2016).
- Soil water: Soil water content was consistently higher under RT compared to CT. This trend has been established since the first season (Mampana, 2014; Swanepoel *et al.* 2013).
- Soil temperature: The soil was cooler under RT, possibly due to a combination of higher water content and surface cover (Mampana, 2014).
- Penetration resistance: Increased soil penetration resistance was measured in the topsoil of the RT treatments (Figure 6). This suggest that a compaction layer developed in the absence of ploughing due to the use of implements such as tractors. This measured increased soil resistance could have a carry-over effect, reducing root development, which in turn compromised crop growth and grain yield. Poorer crop growth resulted in less biomass which compromised the entire CA system.
- Microbial activity: RT had a favourable effect on microbial activity. Clear trends over time were observed in specie richness under RT treatments (Habig and Swanepoel, 2015).
- Mycorrhizae: Initially RT had a positive influence on AM fungal spores in the soil. However, in subsequent years, CT outperformed RT (Sekgota, 2019; Swanepoel *et al.*, 2013).
- Tillage had no effect on nutrients in maize leaves, germination rate, nematodes or glomalin levels (Swanepoel *et al.*, 2013).

Cropping systems:

- Soil nutrient dynamics: Cropping systems had a clearly measurable effect on soil nutrients and affected Ca, K, Mg, NH_4, NO_3, total C and total N. The maize/vetch cropping system was mostly responsible for increased nutrient status in the soil, while maize monoculture or maize/oats intercropping were associated with low nutrient status (Swanepoel *et al.*, 2013).
- Leaf analyses: Initially maize/cowpea was the most beneficial in terms of nutrient uptake, but was outperformed by maize/vetch intercropping towards the end of the trial. The nutrient uptake in leaves also corresponded with crop growth of biomass and yield.
- Aggregate stability: Significant correlations were found between cropping systems and organic C, which in turn significantly influenced aggregate stability and volume (Beukes and Swanepoel, 2016).
- Mycorrhizae: Crop rotation and intercropping with legumes positively affected the number of AM fungal spores in the soil (Sekgota, 2019).

- Cropping systems had a limited effect on nematodes, AM fungi and glomalin levels (Sekgota 2019, Habig and Swanepoel 2015; Swanepoel *et al.*, 2013).

Overall the effect of **fertilizer level** was negligible, however, fertilizer application did have an effect on the following:

- Soil nutrient dynamics: Highly significant changes were measured for soil P under the topsoil (0-5 and 5-10 cm), as a result of high fertilizer application (Swanepoel *et al.,* 2013).
- Leaf analyses: Fertilizer application resulted in significant differences in nutrient uptake for Mg, Ca and K (Swanepoel *et al.,* 2013).
- Mycorrhizae: Higher fertilizer application resulted in higher AM fungal spore counts (Sekgota, 2019; Habig and Swanepoel 2015; Swanepoel *et al.,* 2013).
- Fertilizer had little or no effect on maize grain yield, aggregate stability, nematodes, AM fungi or glomalin levels (Swanepoel *et al.,* 2013; Beukes and Swanepoel, 2016; Sekgota, 2019).

6.2 Minimization of threats to soil functions

Table 22. Soil threats

Soil threats	
Nutrient imbalance and cycle	Significant differences were observed in most years for N, K, Ca, Mg and Na, but these changes were not consistent over time, and each year resulted from different factors (tillage, cropping systems, fertilizer application, or a combination thereof). Cropping systems was mostly responsible for changes in nutrient dynamics, possibly because different crops utilize nutrients differently (Swanepoel *et al.,* 2013).
Soil biodiversity loss	Microbial diversity and activity were higher under no-till than conventional tillage. Fertilizer levels seemed to play a minor role in determining microbial diversity and activity, whereas the cropping systems played a more important role in determining the activity of soil microbial communities. Conservation agriculture yielded the highest soil microbial diversity and activity in diversified cropping systems under no-till (Habig and Swanepoel, 2015).
Soil water management	Increased soil water content was measured under CA treatments, especially reduced tillage treatments (Swanepoel *et al.,* 2013; Mampana, 2014).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Maize yield and biomass production was better under CA during some seasons, while the production was lower during other seasons. This complex dynamic was influenced by factors such as rainfall, compaction, and sequence of cropping systems (Swanepoel *et al.,* 2018). The Zeekoegat CA trial was a dryland, on-station trial. Low and erratic rainfall negatively affected the yields in the last three years of the trial. Periodic drought in critical development periods resulted in overall low yields and biomass. However, we were still able to compare the response of the various treatments under these conditions.

Initially maize grain yield was higher under reduced tillage (2008, 2009 and 2010), but in the last 3 years it was higher under conventional tillage (2011, 2012 and 2013). The overall low yield is contributed to low rainfall and poor rainfall distribution during the growing season. The difference in yield between CT and RT is attributed to topsoil compaction in the RT treatments, due to the absence of tillage. The 6-year average yields between the tillage systems were similar with 2.9 ton/ha for RT and 3.1 ton/ha for CT. Similar to grain yield, the biomass initially performed better under RT, but in the last 3 years CT supported the highest biomass production. As with grain yield, the topsoil compaction under RT reduced root development and disadvantaged the entire crop.

Cropping systems had a significant effect on yield. The CA systems, specifically maize/vetch and maize/cowpea intercropping systems, outperformed conventional practices (monoculture). The trend is that cropping systems had some effect on biomass, although not always significant. Maize monoculture and maize/vetch produced the highest biomass. Maize monoculture produced high biomass because maize was planted in a full stand, and this is compared to maize planted in tramlines. Maize/vetch intercropping produced the most effective soil cover.

Fertilizer had little or no effect on maize grain yield.

6.4 Mitigation of and adaptation to climate change

Carbon sequestration under RT systems was a positive result for mitigation. GHG emissions (CH_4, N_2O) were not measured in this study.

6.5 Socio-economic benefits

Economic effect was measured and expressed as profitability (Rand/hectare) (Figure 7). Profitability was driven by maize yield and rainfall (Swanepoel *et al.*, 2018). Economic comparison between the CA and conventional farming systems indicated that maize monoculture and maize/vetch intercropping were the most beneficial. However, the economic analysis failed to take into account sustainable and long-term use of resources.

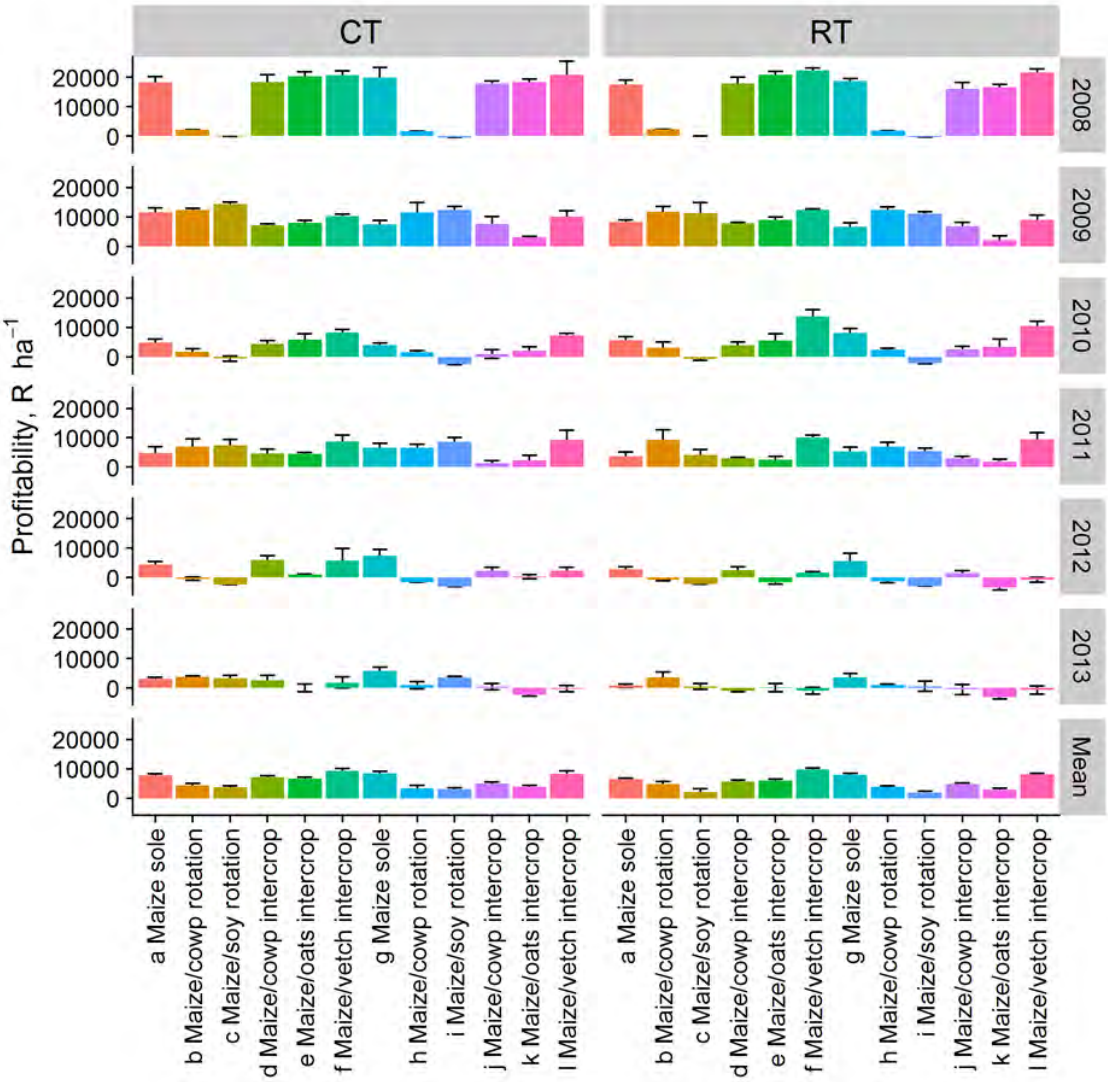

Figure 7. Profitability for 12 farming systems at Zeekoegat expressed in South African Rand per ha

A combination of six cropping systems and two fertilizer levels (system a-f = low fertilizer; system g-l = high fertilizer (for fertilizer levels) and two tillage systems (RT = reduced tillage and CT = conventional tillage, cowp = cowpea, soy = soybean)

6.6 Other benefits of the practice

RT initially resulted in lower weed biomass, but over time this changed, and weed biomass increased under RT, while it stayed similar under CT. A shift in weed species composition was also measured, with CT supporting mainly two dominant pioneer weeds, while weed diversity increased under RT over time (Figure 8) (Baker *et al.,* 2018; Swanepoel *et al.,* 2015; Swanepoel *et al.,* 2013). A combination of manual and chemical weed control was applied regularly. We tested the effect of weed on yields, and found that our weed management was effective and had a negligible effect on the crop yield (Swanepoel *et al.,* 2015). Dominant weed under CT systems were large thorn apple and the dominance of this weed increased over time. Large thorn apple seeds are light activated, and thus germinate after tillage. In the RT treatments, however, the weed seedbank changed over time, with large thorn apple reducing in numbers, replaced by purple nutsedge and perennial weeds (Baker *et al.,* 2018; Swanepoel *et al.,* 2015). Weed biomass sampling occurred a few weeks after planting, prior to the first weeding event (Table 18).

Figure 8. Temporal variation in weed species composition expressed in percentage of biomass.

This under conventional tillage (left) and reduced tillage (right) practices, for the medium-term trial at Zeekoegat.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 23. Soil threats

Soil threats	
Soil compaction	Soil penetrometer resistance (PR) was measured in the sixth season. Higher PR values were found under RT systems, especially in the topsoil. This was a negative tradeoff of CA, which reduced the yield potential (Swanepoel *et al.*, 2013; Swanepoel *et al.*, 2018).

7.2 Increases in greenhouse gas emissions

CO_2 emissions tended to be higher under CT tillage systems compared to RT systems (Figure 9). However, limited measurements were collected.

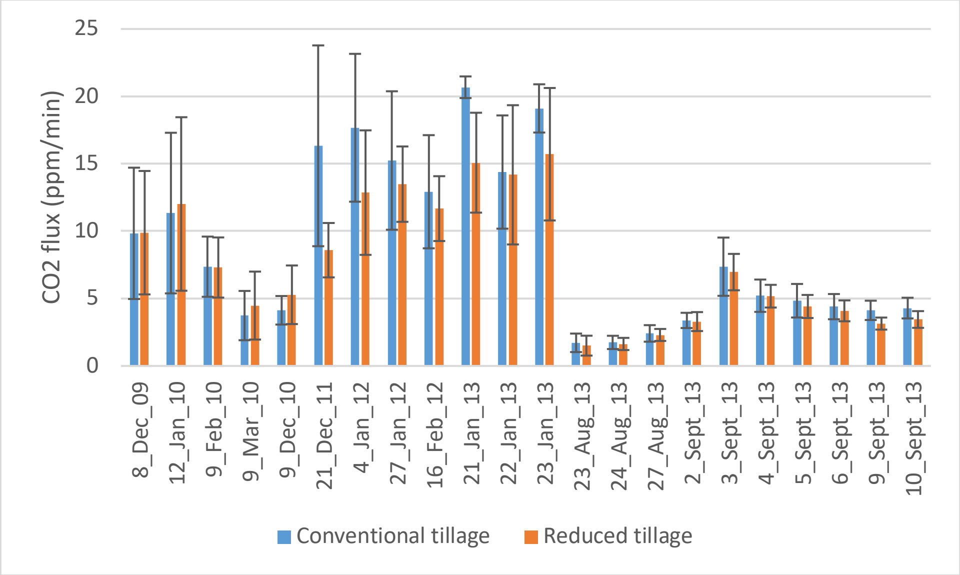

Figure 9. Comparison of CO_2 emission rates under RT and CT (2009 - 2013), black bars represent standard deviation

7.3 Decreases in production (food/fuel/feed/timber/fibre)

Weeds

Weed species composition and weed biomass can change under CA, resulting in potential challenges regarding weed management. Adaptable weed management (where continued monitoring of a system should influence the decision-making process and can be changed as needed, depending on available resources) or integrated weed management (combination of biological, chemical and mechanical weed management) should be practiced for effective weed control. Such weed control programmes can include crop rotation and application of mulch (Swanepoel *et al.,* 2015; Baker *et al.,* 2018).

Compaction

We recorded a negative yield under reduced tillage as time went on. Initially yield and biomass production was higher under RT, but a yield decreased over time was observed. An overall yield decrease in the trial can partly be ascribed to lower rainfall and prolonged dry periods during critical periods in maize development in the last 3 years. However, contrary to what we expected, the RT treatments performed worse than CT under these dry periods. Since soil compaction is one of the potential drawbacks experienced with CA (Swanepoel, Smith and Swanepoel, 2018), we tested the penetrometer resistance (PR), as an indicator of compaction during the last season, to see if PR resistance could explain the difference in the yield. We used a Geotron penetrometer, taking readings every 10 mm up to a depth of 800 mm where possible. The penetrometer was set at a maximum pressure of 4000 kPa. An average of six measurement per plot was taken in 24 plots (12 with RT and 12 with CT), and results were statistically analyzed.

We found significant increased soil penetration resistance in the topsoil of the RT treatments (Swanepoel *et al.,* 2014). We suggest that a compaction layer developed in the absence of ploughing due to the use of implements such as tractors. This increased soil resistance could have had a carry-over effect, reducing root development, which in turn compromised crop growth and grain yield. Poorer crop growth resulted in less biomass which compromised the entire CA system. Values for reduced and conventionally tilled soil were similar up to 50 mm, when a clear increase in resistance was measured under reduced tilled soils. Significant differences were measured between 110-170 mm and again at 310-350 mm (Figure 10) (Swanepoel *et al.,* 2014).

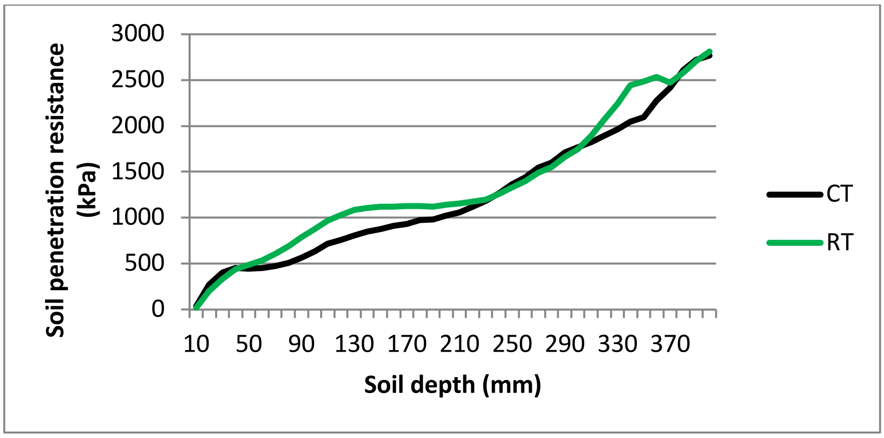

Figure 10. Soil penetration resistance values from RT and CT, at the Zeekoegat field trial

8. Recommendations before implementing the practice

- Soil compaction under reduced tillage is a limitation in some soils. Methods to elevate compaction, such as occasional deep tillage, or rip-on-the-row practices should be implemented in these cases
- Promotion of CA under commercial, and especially small farmers, should focus on advantages, such as food security, sustainability of agricultural resources and improvement of soil quality, rather than financial benefits. Research should align to test and quantify various advantages associated with CA;
- Tailoring of CA to site-specific conditions as the basis for profitability and sustainability will require medium- to long-term trials, in combination with crop modelling to identify optimal site-specifically components, or best management practices of CA;
- Future research could focus on quantifying values of SOC using ecosystem services and natural capital models.

9. Potential barriers for adoption

Table 24. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Soil type and climate highly influence the type of farming and the choice of cropping system (Swanepoel *et al.*, 2018). Resources such as soil type and climate are often one of the most determining factors in successful farming. Higher rainfall regions better support multi-cropping systems that can lead to biomass production that drives the CA system, while arid and semi-arid regions might not have enough available water to produce effective biomass to increase organic matter in the system (Swanepoel *et al.*, 2018a).
Cultural	Yes	Changing mindsets is one of the major limitations Swanepoel, Smith and Swanepoel, 2018).
Social	Yes	Farmers tend to be highly influenced by their farming community, and will be less likely to experiment with CA systems if this is not acceptable practice in their social group (Swanepoel, Smith and Swanepoel, 2018).

Barrier	YES/NO	
Economic	Yes	Maize production and seasonal climate more determine profitability in semi-arid regions, such as RSA, and as a result practicing CA is not always profitable (Swanepoel *et al.*, 2018). Even though CA poses numerous advantages, profitability analysis did not show any significant benefits as a result of CA practices or SOC build-up in the short- or medium-term. The challenge remains to capture the long-term sustainability of CA.
Knowledge	Yes	Knowledge is a major limitation for implementation, as conventional practices change, and farming decisions will have to be made proactive and in response to unexpected changing due to a change in management actions. For this the farmer needs to understand the farming system, be aware of early warning signs, and have resources at their disposal to respond (Swanepoel, Smith and Swanepoel, 2018b).

Photos

Photo 11. Zeekoegat CA trial included cropping systems treatments

Such as maize-cowpea rotation (left) and maize-cowpea intercropping (right).

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6. Intercropping grain legumes and cereals in Africa

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1. Related practices

Intercropping grain legumes and cereals, N fertilization, No-till

2. Description of the regional case study

A meta-analysis was conducted across Africa to quantify the extent of soil organic carbon (SOC) sequestration when intercropping grain legumes and cereals is used. Based on 73 pairs of comparisons between intercropping and its cereal monocropping control from 18 studies, intercropping increased SOC concentration by ~15%. Through nitrogen (N_2) fixation, mobilization of recalcitrant nutrients, and addition of organic material to the soil, legumes play a critical role in maintaining soil productivity in low-input farming systems. By adding diversity and N to the system, intercropping systems generate greater root biomass production. Carbon sequestration, which is enhanced by N_2 fixation, can positively influence SOC accretion and soil quality over time. The C sequestration property of an intercropping system is further supported by intercrop's ability to reduce soil erosion by ~46%, based on a meta-analysis of 10 and 13 data pairs from 6 studies, suggesting runoff and sediment reduction with intercropping (Daryanto *et al.*, 2020). Variability of SOC stock, however, occurred with climate (e.g. dry or wet), soil (e.g. clay or sand), and management (e.g. with or without crop residue incorporation). Drier climate or sandier soils, for example, tends to accumulate lower SOC. We highlighted the advantage of adding legumes to cereal farming for maintaining soil fertility, a crucial foundation to achieving sustainable agricultural production.

3. Context of the case study

This study covers 18 studies from the following countries across continental Africa: Ghana, Kenya, Zimbabwe, the United Republic of Tanzania, Malawi, Nigeria, Swaziland, Niger, South Africa, Benin, Mali, and Ethiopia.

The climate, based on Intergovernmental Panel on Climate Change (IPCC) climate zone, range from a warm temperate dry climate, with mean annual rainfall (MAP) of 570 mm to tropical moist, with a MAP of 1200 mm.

4. Possibility of scaling up

Since the study is a meta-analysis, the overall results are already scaled-up. However, there is variability in the individual studies, depending on climate, soil, and management (Table 25).

5. Impact on soil organic carbon stocks

In Africa, intercropping increased SOC concentration by ~15% compared to sole cropping (monocropping) (Daryanto *et al.*, 2020). Our meta-analysis also suggested a significantly much higher increase in SOC concentration (35%) when cereal plants did not receive N fertilizer compared with those receiving N fertilizer (6%). Nitrogen fixation is generally suppressed by high availability of mineral N (Pelzer *et al.*, 2014), which could influence the overall performance of the intercropping system. The ability of intercropping system to accrue SOC without supplementary N to the cereal crops would therefore be its paramount property to improve soil quality in Africa.

But since very few studies reported their bulk density, here we reported site-specific examples (Table 25) of SOC stock in predominantly sandy soils (clay content <15%) of different African regions whose bulk density ranged from 1.2 g/cm^3 to 1.68 g/cm^3 across depths (up to 30 cm). Taken an example by Kombiok and Clottey (2003), SOC stock was calculated by multiplying SOC concentration with its bulk density. The SOC concentration is 0.77% (7.7 g SOC/kg soil) in the intercropping and 0.52% (5.2 g SOC/kg soil) in the monocropping system; both are in the top 20 cm of soil. With bulk density of 1.45 g/cm^3 (Baba *et al.*, 2013), we obtained an SOC stock of 22.4 t/ha (intercrop) and 15.0 t/ha (monocrop) over two years. Subtracting 15 t/ha from 22.4 t/ha and dividing the number by two results in a sequestration rate of 3.7 tC/ha/yr. This number is considered very high; the incorporation of legume (mucuna) biomass might be responsible for such result.

Except for the study by Kombiok and Clottey (2003) above, the potential annual SOC stock accrual in other studies ranged from 0.3 to 1.3 tC/ha/yr where no fertilizer N was applied (Table 25). This range is similar to a global study indicates that in western-central (e.g. Benin, Nigeria, Mali, Ghana), and east-southern Africa (e.g. Kenya, South Africa), the annual increase of SOC is around 0.58-1.19, 0.55-1.13 tC/ha/yr under medium-high sequestration scenarios (Zomer *et al.*, 2017).

In another example, we found SOC declines despite the application of intercropping (Swanepoel *et al.*, 2018). Sandy soils and erratic rainfall usually foster C decomposition, and in cases where SOC declines are observed, it is likely that easily decomposable legume residues stimulates the mineralization of SOC (Barthès *et al.*, 2004). Intercropping also cannot immediately offset the loss of SOC when native lands are converted into cultivated lands. In contrast, higher-than-average rainfall that can happen during an experimental period can promote crop growth, generating higher-than-average SOC accumulation.

Table 25. Some of the intercropping results across Africa showing the changes of SOC (up to 30 cm deep) without the addition of N fertilizer to the cereals

Location	Climate zone	Soil type	Baseline (monocrop) organic C stock (tC/ha) with tillage method	Additional C storage (tC/ha/yr)	Duration (Years)	More information	Reference
Intercropping without addition of N fertilizer to the cereals							
Mali	Warm temperate dry (MAP = 570 mm)	Sandy (>80% sand, <15% clay)	48.4 (0-15 cm), hand hoeing	1.1 (0-15 cm, no crop residue incorporation to the soil)	3	Millet (*Pennisetum glaucum* (L.) R.Br. cv. Toroniou) and cowpea (*Vigna unguiculata* L. cv. IT89DK-245)	Samake *et al.* (2006); Samaké (2003)
Kenya	Tropical dry (MAP = 760 mm)	Kandic Rhodustalfs (Alfisols, USDA), sandy clay loam (32% clay and 54% sand)	24.8 (0-15 cm), hand hoeing	0.3 (0-15 cm, no residue)	5	Maize (*Zea mays* L. cv. 'Katumani composite') and pigeon pea (*Cajanus cajan* (L.) Millsp. cv. 'ICP 13155' or 'Katumani 81/3/3)	Kwena (2018); Rao and Mathuva (2000)
Ghana	Tropical moist (MAP = 1200 mm)	Ferric Luvisol (FAO-UNESCO), sandy loamy	15.0 (0-20 cm), with residue	3.7 (0-20 cm)	2	Maize (*Zea mays* L. cv. Obatampa and velvet bean (*Mucuna pruriens* (L.) DC.)	Baba *et al.* (2013); Kombiok and Clottey (2003)
Benin	Tropical moist (MAP = 1200 mm)	Typic Tropudults (USDA) or Dystric Nitosols (FAO) with sandy loam texture (12.8% clay)	14.5 (0-20 cm), hand hoeing	1.3 (0-20 cm, with residue)	11	Maize (*Zea mays* L. cv. DMR and velvet bean (*Mucuna pruriens* (L.) DC.)	Barthès *et al.* (2004)
Intercropping with addition of N fertilizers to the cereals							
South Africa	Warm temperate dry (MAP = 870 mm)	Rhodic Nitisol (IUSS Working Group WRB, 2014) with 44% clay (0-10 cm)	19.3 (0-10 cm, conventional tillage), 23.2 (0-10 cm, reduced tillage)	-0.1 (0-10 cm, CT), -0.25 (0-10 cm, RT with residue)	6	Maize (*Zea mays* L. cv. Pannar 6 P/110) with 70 kg N/ha and cowpea (*Vigna unguiculata* L. unspecified cultivar)	Swanepoel *et al.* (2018)
Ghana	Tropical moist (MAP = 1026 mm)	Ferric Lixisols (FAO) or Alfisols (USDA), with sandy texture (low clay content)	14.8 (conventional tillage or CT), 18.8 hand hoeing), 27.2 (no tillage or NT)	1.5 (CT), 0.4 (hand hoeing), -0.25 (NT) (all with residue)	4	Maize (*Zea mays* L.) variety cv. Obatanpa with 314 kg N/ha, and soybean (*Glycine max* L. Merril) variety cv. Jenguma)	Naab *et al.* (2017)
Nigeria	Tropical moist (MAP = 1137 mm)	Sandy loam (13% clay)	15.8	1.6 (0-30 cm, (no information about residue)	2	Maize (*Zea mays* L. with 50 kg N fertilizer and mucuna (Mucuna *pruriens* (L.) DC.)	Agber and Anjembe (2012); Shave, Ter-Rumum and Enoch (2012)

CT: Conventional tillage; RT: Reduced tillage; NT: No-till

5. Other benefits of the practice

5.1. Improvement of soil properties

There is evidence showing that compared to monocropping, intercropping increases in soil aggregate stability and porosity, increases root biomass, exudates production, and mycorrhizal colonization (Mathan, 1989).

5.2 Minimization of threats to soil functions

Table 26. Soil threats

Soil threats	
Soil erosion	Intercropping can reduce runoff and erosion as there are more cover that intercepts the kinetic energy of rainfall and protect soil aggregates (Nyawade *et al.*, 2018).
Nutrient imbalance and cycles	Legume residues are relatively rich in N with low C:N ratio, favoring rapid decomposition and subsequent release of N. Some legumes can to mobilize recalcitrant forms of P (Franke *et al.*, 2018) and increase the availability of K, Fe, Zn, and Mn (Inal *et al.*, 2007; Li *et al.*, 2014).
Soil acidification	While legume can induce soil acidification, a decline in soil pH should be less of a concern in combination with cereal. Moreover, decomposition of legume residues help to increase pH (Tang and Yu, 1999).
Soil biodiversity loss	Intercropping can increase soil biodiversity as plant diversity determines of soil biodiversity (biodiversity begets biodiversity) (Eisenhauer, 2016).
Soil water management	Intercropping confers resiliency to rainfall variability as suggested by the lack of LER (land equivalent ratio) difference between wet and dry years (Daryanto *et al.*, 2020). Double vegetative layer improves the proportion of soil water transpired compared to the evaporative demand from soils. Some cereals (e.g., sorghum or pearl millet) uses water and intercepted solar radiation more efficiently when water is limited (Runkulatile *et al.*, 1998). Pigeon pea can even supply water to the intercropped maize via hydraulic lift, a process that can be further enhanced when the pigeon pea is shaded (Sekiya and Yano, 2004).

5.3 Increases in production (e.g. food/fuel/feed/timber)

Intercropping grain legumes and cereals do not guarantee a transgressive overyielding (i.e., total yield of the intercrop is greater than the highest yield among the sole crop). However, we might expect an increase in cereal productivity (when additive density is used) with a generally positive relationship between cereal yields and cereal pLER (partial Land Equivalent Ratio) (Daryanto *et al.*, 2020).

5.4 Socio-economic benefits

Both labor and variable costs are higher in the intercropping than monocropping system as farmers need to purchase and plant legume seeds. Selecting grain legumes that can be ratooned, such as pigeon pea can minimize such cost while farmers can safeguard their household food availability and income while providing diverse food sources (Rusinamhodzi, Makoko and Sariah, 2017). But in areas where *Striga* dominates, the integration of *Desmodium* to intercropped cereals and grain legumes is highly recommended to gain the most benefits from intercropping. It can increase revenue to farmers by ~78 percent per growing season, with only ~10 percent of an additional cost (both labor and variable cost) (Khan *et al.*, 2009).

6. Potential drawbacks to the practice

6.1 Tradeoffs with other threats to soil functions

Table 27. Soil threats

Soil threats	
Nutrient imbalance and cycles	In regions with low soil fertility, intercropping legumes into low-input cereal farming system may not show immediate result in improving soil fertility due to high nutrient demand of the cereals (Kwena, 2018).
Soil acidification	See Section 5.2.
Soil compaction	Soil compaction associated with no-till can reduce yield (particularly cereals) (Swanepoel *et al.*, 2018).
Soil water management	With intercropping, combination of species needs to be carefully selected. Pearl millet, which shares the same rooting depth and has overlapped canopy architecture with cowpea, may compete for water and light and eventually impact yield (Nelson *et al.*, 2018). Intercropping grain legumes to cereal can also decrease deep soil moisture, because cereal crops, when competing for water, can develop deep roots to avoid drought. The roots of pearl millet and sorghum, for example, can reach as deep as 1.85 m (Stone *et al.*, 2001; Zegada-Lizarazu *et al.*, 2006).

6.2 Decreases in production (food/fuel/feed/timber/fibre)

There are possibilities of competition for resources (e.g. water, light), which may influence yield. For example, when pearl millet is intercropped with cowpea, they share the same rooting depth and have overlapped canopy architecture (Nelson *et al.*, 2018).

7. Recommendations before implementing the practice

Although in general intercropping is beneficial for soil, the extent of SOC accumulation is affected by management (e.g. no-tillage, residue incorporation), climate and soil type. Inadequate plant biomass often becomes the factor leading to SOC declines despite intercropping practice, as opposed to higher-than-average rainfall that supports biomass production (Naab *et al.*, 2017; Swanepoel *et al.*, 2018).

8. Potential barriers for adoption

Table 28. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Preference for grain legumes varied between locations in Africa and factors such as grain characteristics and farmers' culinary preferences need to be considered if a new species to be introduced (Schulz *et al.*, 2003)
Economic	Yes	Both labor and variable costs are higher in the intercropping than monocropping system as farmers need to purchase and plant legume seeds (Khan *et al.*, 2009).
Knowledge	Yes	Education and proximity to extension services contributed significantly to farmers' knowledge, suggesting continuous training and capacity building are essential for achieving sustainable farming management (Abtew *et al.*, 2016).
Other	Yes	Farmers rely on local market for seed, which can be a barrier for initial cropping season (McGuire and Sperling, 2016)

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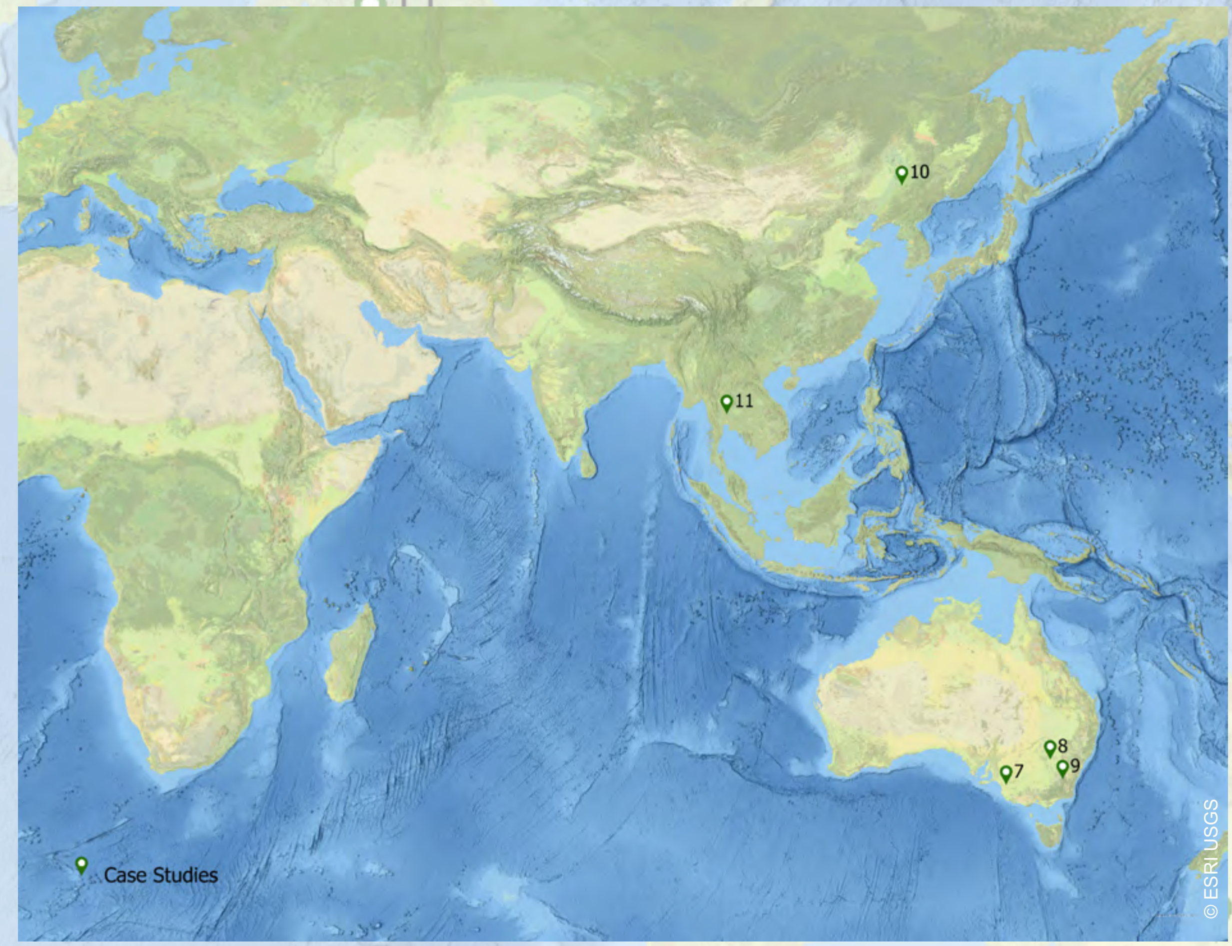
Asia and Southwest Pacific



Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
7	Pacific	Selection and introduction of dung beetles to beetle-depauperate regions in Southern Australia	Insect introduction			10 months
8	Pacific	Irrigated cotton cropping systems in Australian Vertisols under minimum tillage	Reduced tillage	Crop rotations	Fertilization	4 to 20
9	Pacific	Grazing management in rangeland grassland systems in South and East Australia	Rotatonal grazing			4 to 10
10	Asia	16 years of no tillage and residue cover on continuous maize in a black soil of China	No-till	Mulching		16
11	Asia	Rice straw mulching, charcoal, and no-tillage on maize in Lopburi, Thailand	No-till	Mulching	Organic matter additions	4

7. Selection and introduction of dung beetles to beetle-depauperate regions in Southern Australia

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1. Related practices

Selection and introduction of dung beetles to beetle-depauperate regions to bury the dung of domestic stock.

2. Description of the case study

This case study illustrates the process of importing and establishing winter- and spring-active dung beetles in Southern Australia in a beetle-depauperate region and demonstrates increased soil organic carbon (SOC) in response to dung burial by winter- and spring-active dung beetles. The amounts and persistence of carbon lodged in the soil by deep-tunnelling (to 50 cm) beetles were measured in two studies (Doube, 2008; Doube and Dale, 2012). Both studies (in a warm temperate dry Intergovernmental Panel on Climate Change (IPCC) climate zone in South Australia) examined the capacity of the introduced southern European beetle *Bubas bison* to increase levels of soil carbon in pasture and conclude that the deep-tunnelling dung beetle *B. bison* transferred substantial quantities of dung 30–50 cm into the soil profile and resulted in a significant increase in soil carbon in the short (10 months) (study 1, Table 29, Doube and Dale, 2012) and the medium term (2 years) (study 2, Table 30, Doube, 2008).

Across temperate Southern Australia, clear winter and spring gaps in dung burial were recognized in the 1960s (Edwards, 2007). Climate matching of temperate Southern Australia with southern Europe and southern Africa identified suitable donor regions and a range of candidate species were identified, including the winter-active species *B. bison* and the spring-active species *Onthophagus vacca* and *Bubas bubalus*. Secure quarantine procedures were outlined and government permission to import these species into Australia was obtained.

Between 1980 and 1986 *B. bison* and *O. vacca* and were field collected in Europe, reared in the laboratory, and their eggs sent to the Commonwealth Scientific and Industrial Research Organisation (CSIRO) laboratories in

Canberra. Both species were difficult to rear but adult *B. bison* were released in two cohorts (1983, n=527; 1986, n=586) at different locations the south-west of Western Australia (WA): the species established and became locally abundant in the 1990s (Edwards, 2007). Small numbers of *O. vacca* were reared and released to the field in the mid-1980s but failed to establish. Adult *B. bubalus* were brought to Australia in the early 1990s but only small numbers of F_1 beetles were reared and none were released to the field (Steinbauer and Wardhaugh, 1993).

With *B. bison* firmly established in WA, it was then necessary to redistribute the species throughout southern WA and in the eastern states. Field cropping occurred over the next 25 years and hundreds of thousands of beetles were relocated, initially from WA but subsequently from numerous regions of high abundance in the eastern states. Introductions to the Fleurieu Peninsula, South Australia, provide an illustration of the process. The first field releases (25 colonies, each of 1 000 beetles) took place in 2002 and 2003. By 2007, the species had established in numbers of locations but had not spread far. By 2015 it had become widespread but was missing from two regions that appeared suitable, and so 20 colonies (20 000 beetles) were released into these regions in 2017. By winter 2018 *B. bison* was breeding at all release sites (Doube, 2018a). The species is now widespread across Southern Australia.

Revival of interest in re-introducing spring species led to a series of Meat and Livestock Australia (MLA)-funded projects in which *O. vacca* and *B. bubalus* were re-introduced from Europe and the rearing problems were partially solved (Wright, Gleeson and Robinson, 2015). Small numbers of laboratory-reared beetles were transferred to high-care field cages, where they bred successfully (Doube, 2018b).

A major multi-agency program (Dung Beetle Ecosystem Engineers: DBEE) followed (2017–2022) but laboratory mass rearing remained a problem and few beetles were available for field release two years into the program. Fortunately, a privately funded program (run by Creation Care Pty Ltd), using stock from the original MLA program, successfully reared moderate numbers, some of which were used by DBEE to establish successful on-farm field nurseries (50 adults per nursery) in cool, moist environments. Creation Care had undertaken a detailed study of the behaviour and the temperature / moisture requirements of these beetles and developed a highly successful field nursery program (with 100 beetles per field cage) (G. Dalton, personal communication, 2020). It is likely that *O. vacca* and *B. bubalus* are now firmly established in a small number of locations. The next task is to disperse them across the southern part of the continent.

3. Context of the case study

A suite of 23 species has been established in Australia and summer- and winter-active species are now common in Southern Australia (Edwards, 2007). A clear spring gap has been addressed by the re-introduction of *O. vacca* and *B. bubalus*. A new list of candidate species for Australia is currently being drawn up (Dung Beetle Ecosystem Engineers, personal communication, 2020).

However, in the past there have been many expensive failures. For example, during 1965–1985, only 23 of the 53 species brought to CSIRO established in the field: the reasons for the numerous failures are explored by Edwards (2007) and include poor habitat matching and problems with mass rearing the beetles in the laboratory and the subsequent release of low numbers of some species to the field.

The Australian experience suggests that the release and establishment of new dung beetle populations in the field has rarely been successful unless 1 000 or more beetles are released into a favourable environment. CSIRO data on the beetle releases undertaken during the original dung beetle program (1965–1985) illustrate this problem (Edwards, 2007). For example, 14 species that were released but failed to establish had an average 841 beetles released per species. In contrast, thousands of individuals of most of the successful species were released but, even then, some failed to establish; for example, *Copris fallaciosus* (6 090 released), *Copris incertus* (2 973), *Onitis crenatus* (4 083) and *Onitis westermanni* (7 514). Success appeared to require the release of thousands of laboratory-reared beetles and of course unfavourable environments needed to be avoided. For example, in Mediterranean Southern Australia the introduced European *B. bison* does not survive in regions of deep sand or in regions with wet summer soils (Doube and Marshall, 2014).

Where possible, it has been common practice to release about 1 000 winter beetles in each starter colony, and this has proved successful. However, in the 2017 Fleurieu Peninsula beetle releases, an initial inoculum of 2 000 beetles appeared to be considerably more successful (as indicated by 2018 beetle activity) than an initial inoculum of 1 000 beetles, suggesting that field releases of several thousand beetles per location might be a more efficient use of beetles, provided that the environment was suitable (Doube, 2018a). Where field harvesting of large numbers is readily achieved, (e.g. some summer beetles are found at densities of thousands per dung pad (Ridsdill-Smith and Edwards, 2011), starter colonies containing thousands of beetles have been released.

Target species that are difficult to rear in the laboratory are likely to be available for release in only low numbers, and so field releases may fail. The recent Australian DBEE program has resolved this problem with targeted 'on-farm' releases of 50–100 beetles per field cage, rather than 1 000+ per release site. Beetles are confined to the field cages and in suitable environments can breed up quickly, enabling subsequent release of considerable numbers at those sites. Five species (*O. vacca*, *B. bubalus, B. bison, Onitis caffer* and *Onthophagus taurus*) have been reared successfully in field cages. Failure to breed in field cages can help define the natural limits of introduced species.

The importance of systematic investigation to understand the reproductive biology of 'difficult' species and their environmental requirements has been demonstrated by the DBEE program and Creation Care in the successful implementation of on-farm nurseries for spring-active species at many sites across southern Australia.

4. Possibility of scaling up

This application can be scaled up in a number of ways:

- scaling up mass rearing facilities and on-farm mass rearing of recently introduced species; for example, speeding the redistribution of *B. bubalus* and *O. vacca* across southern Australia;
- scaling up field cropping and redistribution;
- redistributing successfully established species to new receptor countries; for example, taking *B. bison* from Australia to the Americas; and
- identifying new gaps and new species to fill those gaps.

The widespread implementation of these processes requires substantial international financial support to apply the practice to regions deficient in appropriate dung beetle species. The process of identifying candidate species appropriate for target regions is expensive and time consuming and there will be barriers related to compliance with the Nagoya Protocol (Secretariat of the Convention on Biological Diversity, 2011) and to protecting the biodiversity of the dung and soil fauna in the target region.

4.1 Scaling up local mass rearing and release

The original CSIRO dung beetle program (1965–1885) used glasshouse nurseries to rear hundreds of thousands of readily reared species (those without developmental issues, such as diapause) (Edwards, 2007). Mass rearing the next cohort of new species is likely to prove more problematic because most of them have developmental constraints that require resolution.

Australia, with the DBEE program and the activities of Creation Care, provides a good example of scaling up local mass rearing and release of 'difficult' species. Initially small-scale field nurseries were established (Photo 12). Following success with both *B. bubalus* and *O. vacca* Creation Care developed larger nurseries (Photo 13) and then substantial hoop houses (stage 3 in Photo 12) (now used by DBEE) for the mass production of both species in a confined and controlled environment. With moderate numbers (thousands) available from hoop-house rearing, Creation Care will, from spring 2021, provide a commercially available on-farm nursery kits for *O. vacca* and *B. bubalus* (with support for the first 15 months) (G. Dalton, personal communication, 2020). This high-care system should substantially increase the probability of establishing new species and increase the rate at which they can be dispersed across the landscape.

4.2 National redistribution of successful species

Several private enterprises have developed viable commercial businesses cropping and redistributing established species in Australia. This activity has been successful in spreading numbers of species throughout the landscape. In addition, several publicly funded cropping and redistribution exercises (Tyndale-Biscoe, 1990) and grower-initiated programs have contributed to this redistribution. For example, a bus load of farmers from Tasmania went to mainland Australia (Braidwood) and collected thousands of *Geotrupes spiniger* (Kershaw and Stevenson, 2002). These are the ancestors of the millions of this species that now populate northern Tasmania.

Most introduced species in Australia have largely reached the natural limits of their distribution, which can be viewed in the distribution maps in Edwards, Wright and Wilson (2015) but others (e.g. *O. caffer* and two *Copris* species) are far from that goal and need to be redistributed more widely. The newly introduced species *O. vacca* and *B. bubalus* may well be available for field cropping and redistribution in the near future.

4.3 International redistribution of successful species

Substantial international scaling up of this process is readily achievable. The European distribution of *B. bison* and its sister species *Bubas bubalus* and *Bubas bubaloides* is well understood and we anticipate a substantial capacity of these species to colonize Mediterranean-climate pastures in North and South America and other regions.

There is substantial potential to upscale the introduction and redistribution of the summer-active *Onitis* and *Onthophagus* species to many land masses around the world. Other genera also contain candidate species.

The methods outlined above for the redistribution of dung beetle species are widely applicable.

4.4 Identifying new gaps and candidate species to fill them

The task of identifying seasonal and geographic gaps in dung beetle activity requires a detailed analysis of the literature and then on-ground monitoring in target locations. Similar activity is required in relation to potential donor countries. A review of the current literature needs to be commissioned.

Upscaling this activity to an international program will require substantial funding and serious collaboration with the agricultural/environmental agencies in donor and receptor countries.

5. Potential of C sequestration / Potential of additional storage

5.1 Beetle-induced deep soil increases in soil organic matter (SOM)

The published literature describing the effects of dung beetle activity on soil carbon has been limited to endocoprid beetles (which do not bury dung) and shallow-burying tunnellers: only minor effects on soil carbon levels were detected. In marked contrast, deep-tunnelling beetles substantially increase the amount and persistence of carbon in the soil profile (Doube 2008; Doube and Dale 2012).

In study 1, *B. bison* was allowed to bury dung in soil cores (buried soil-filled mesh bags with a natural soil profile, and with and without dung burial) in the field (a Brown Kurasol) and the carbon present in different soil factions was assessed (Table 29). About 50 percent (containing about 150 g carbon) of each 3 kg (wet weight) dung pad was buried (Doube and Dale, 2012). This dung burial resulted in an increase of 70 g of carbon in the soil profile after ten months (Table 30), which equates to 45 g per kg of buried fresh dung. This was considered to be due to the addition of dung carbon to the soil and the prolific growth of plant roots into the dung-affected subsoil. A parallel, second set of dung pads was set up on undisturbed ground adjacent to the buried soil cores and sampled at the same time (Doube and Dale, 2012). There was no significant difference in the carbon levels in the control (no dung) carbon data from the disturbed and undisturbed environments, indicating that the control data in Table 29 provide an estimate of the baseline soil carbon levels (approximately 30.5 t C per ha to 50 cm). Ten months after its burial, 47 percent of the carbon in buried dung (that is, 70 g out of 150 g) remained in the soil, the remainder being metabolized by microbes and lost to the atmosphere through 'microbial respiration', releasing water-soluble plant nutrients to the soil which, in turn, increased pasture production and provided a corresponding increase in the deposition of root carbon (Doube, 2008). In contrast, only 17 percent of the carbon in the control unburied surface pad (that is, 51 g out of 300 g Table 30, Practice Document Volume 3) remained in surface residues after 10 months.

In study 2, levels of soil carbon in the subsoil (20–50 cm) in soil cores were examined following dung burial by *B. bison* over two years in two contrasting pasture soils in South Australia (a Black Dermasol and a Brown Kurasol) (Hall, Maschmedt and Billing, 2009; Isbell and NCST, 2021).. The closest to these soil types in the USDA Soil Taxonomy system are Ultisols and Inceptisols, respectively (Hughes *et al.*, 2018). There was no significant change over time (11–24 months after dung burial) in subsoil carbon in the soil cores with buried dung in either soil type, and the subsoil carbon in these cores was on average 69 percent higher than in the controls (with no buried dung) in a clay soil (the Black Dermasol: soil type 1) and 25 percent higher than the controls in a duplex soil (the Brown Kurasol: soil type 2), possibly reflecting the effect of soil type on the retention of SOM in the soil profile.

Table 29. Organic carbon levels (%) of the component parts of the soil cores in trial 1 after 10 months

Soil core component	Dung + beetles	Dung-only	Controls
Surface litter	2.6 ± 0.7	4.1 ± 0.3	1.3 ± 0.2
Upper section	0.99 ± 0.26	0.86 ± 0.07	0.72 ± 0.09
Basal section	0.69 ± 0.07	0.46 ± 0.25	0.58 ± 0.07
Tunnels + contents	1.31 ± 0.20		
Mean±SD dry weight of soil cores (kg)	28.8 ± 3.5	25.2 ± 2.8	23.6 ± 2.9

Source: (Doube and Dale, 2012)

Table 30. The organic carbon (%) concentration in the subsoil (20–45 cm) in trial 2

	August 2006		November 2006		May 2007		September 2007	
Treatment	Soil type 1*	Soil type 2**	Soil type 1*	Soil type 2**	Soil type 1*	Soil type 2**	Soil type 1*	Soil type 2**
Controls subsoil	2.01	0.68	2.02	0.85	2.14	0.70	2.11	0.61
Dung-only subsoil			2.23	0.88	1.94	0.74	1.97	0.67
Total dung+beetles subsoil	2.56	1.10	2.66	1.54	2.54	1.21	2.55	0.97
Dung+beetles: tunnels+environs		4.12	7.20	4.25	4.80	2.70	3.35	1.38
Dung+beetles: remainder		0.79	2.27	1.20	2.49	1.15	2.32	0.89

Source: (Doube, 2008)

*a Black Dermasol; **a Brown Kurasol

These two studies indicate the potential of deep-tunnelling dung beetles to increase levels of SOC but a much wider analysis is required to support extrapolation (see below) to other environments.

5.2 How much SOC can be sequestered by Bubas species in southern Australia?

At 1.5 beasts per hectare, cattle will produce about 6 000 L of dung over 200 days (the *Bubas* activity season). If all that dung were buried and each litre increased soil carbon by 45 g, there would be an annual increase of 0.27 tC/ha, or about 0.9 percent of the total stock of soil carbon to 50 cm. This is of a similar order of magnitude to the increases in soil carbon levels induced by a combination of direct drilling and stubble retention in cropping systems (less than 1 percent of the total stock) (Edwards, 2020). The primary productivity of both cropping and grazing systems is similarly limited by soil moisture, plant species and soil fertility. The return to the soil of the 'waste' organic matter (stubble and dung) provides the fuel for increasing SOC levels. It is therefore no surprise that grain stubble and dung produce a similar annual increase in soil carbon, although the stubble is primarily a surface phenomenon while dung burial affects the subsoil, which has a considerable capacity to absorb organic carbon (Hoyle *et al.*, 2013).

6. Other benefits of the practice

The improvements in soil properties brought about by dung burial by dung beetles and the threats posed to the soil are summarized in Nichols *et al.* (2008), Ridsdill-Smith and Edwards (2011), Doube and Marshall (2014) and Doube (2018c) (see Practice Factsheet n°20 "Dung burial by beetles" Volume 3).

6.1 Improvement of soil properties

Dung burial by beetles generates tunnels into the soil and deposits substantial amounts of organic matter through the soil profile. The beneficial impacts of such burial by *B. bison* are demonstrated by Doube (2008) and Doube and Dale (2012) and include dramatically improving the physical, chemical and biological properties of soil. The physical benefits include improved soil aeration, reduced bulk density and improved water infiltration. The chemical benefits include increased cation exchange capacity, improved soil pH and increased plant nutrients and carbon throughout the soil profile. The biological benefits include increased microbial activity, increased plant root growth and more earthworms.

6.2 On minimizing soil threats

These issues have been considered in Practice Factsheet n°20 "Dung burial by beetles" Volume 3.

6.3 On production (e.g. food/fuel/feed/timber/fibre)

Doube (2008) demonstrated a 20+ percent increase in pasture production in response to dung burial by *B. bison*.

6.4 On climate change mitigation and adaptation

The levels of carbon storage in southern Australian soils that might arise from dung burial by two introduced deep-tunnelling *Bubas* species (the winter-active *B. bison* and the spring-active *B. bubalus*) can be estimated, but with serious caveats. If these beetles were widespread across moist southern Australia and buried 50 percent of the dung produced by five million cattle in the region, each producing 20 kg of fresh dung per day over 200 days per annum, then a total of approximately ten million tonnes of fresh dung would be buried annually. If the affected soil retained an extra 45 g of carbon per kg fresh dung buried, the soil carbon store could be increased by 400 000 tonnes of carbon, or 1.7 $MtCO_{2e}$, annually, approximately equivalent to 2 percent of the total annual greenhouse gas emissions from agriculture in Australia (Bourne *et al.*, 2018). Other tunnelling species are well established across the moister regions of north and southern Australia and bury additional (but unquantified) amounts of dung.

6.5 Socioeconomic benefits

These issues have been considered in Practice Factsheet n°20 "Dung burial by beetles" Volume 3.

7. Tradeoffs or conflicts with other practices

These issues have been considered in Practice Factsheet n°20 “Dung burial by beetles” Volume 3.

8. Potential barriers for adoption

Potential barriers for adoption that apply to this case study are evidenced in Practice Factsheet n°20 “Dung burial by beetles” Volume 3.

Photos


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Stage 1


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Stage 2

Stage 3

Photo 12. The three stages in the development of field nurseries

Photo 13. A field cage for on-farm rearing of dung beetles

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8. Irrigated cotton cropping systems in Australian Vertisols under minimum tillage

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1. Related practices

Minimum tillage, crop rotations, mineral fertilization, adequate irrigation practices

2. Description of the case study

In Australia, irrigated cotton (*Gossypium spp.*) is mostly grown on Vertisols (shrinking and swelling medium–high clay soils) and is characterized by 1) mechanized farming with heavy machinery that may cause compaction, 2) genetically modified (GM) cotton where soil disturbance after harvest is mandatory to destroy *Heliothis spp.* moth pupae ("pupae busting"), 3) high nutrient input, predominantly through mineral fertilizers, 4) cereal or legume crop rotations that improve soil health, water and economic productivity, and 5) closed irrigation networks that require desilting at regular intervals. SOC sequestration in cotton growing soils may be constrained by sodicity and soil compaction which inhibit crop growth due to waterlogging when soils are wet and high soil strength when dry. Intra-aggregate dispersion in sodic soils also reduces C stabilisation and protection, a key mechanism of SOC sequestration. Historically, conventional cotton farming systems were characterized by monoculture, raking and burning cotton stubbles at the end of each season and aggressive tillage operations with heavy machinery, all of which were detrimental to soil health and soil organic carbon stocks. Because cotton generates a higher gross margin than many other annual crops (Nachimuthu *et al.*, 2017), many growers preferred to plant cotton annually (cotton monoculture) rather than rotating with another crop. The management practices reported in this case-study were aimed at developing a climate-resilient cropping system that improved soil health and minimized its environmental footprint. This case study focuses on minimum tillage in cotton cropping systems by summarizing results from long and short-term experiments that assessed soil quality, greenhouse gas emissions and terrestrial hydrological pathways and their role in soil C fluxes.

3. Context of the case study

This case study is specific to Australian irrigated cotton farming systems that incorporate cotton-cereal or cotton-legume rotations. The data presented in this case study is relevant to warm temperate dry to warm tropical dry climatic conditions.

4. Possibility of scaling up

This case study is specific to high activity clay soils (Vertisols) with strong shrinking and swelling characteristics and represents ~75 percent (Hulugalle and Scott, 2008) of the Australian irrigated cotton industry.

5. Impact on soil organic carbon stocks

Australian agriculture and change in land use from natural vegetation or pasture to cropping land is more recent compared to other countries. Storage of SOC in Australian cotton farming systems follows a two-stage process. Upon conversion of land to irrigated cropping, there is an initial rapid decline in SOC stocks, followed by a reduction in the rate of decline or an increase in SOC sequestration rates. The initial decline in SOC is a direct result of the change in land use from native vegetation or pasture to cropping as the differences in C inputs and degradation processes drive the system to a new equilibrium. After reaching the new lower SOC equilibrium, some potential for increased SOC sequestration exists with the adoption of conservation agricultural practices such as minimum tillage, sowing a rotation crop and minimizing bare fallow (cotton-cereal-cover crop rotation) (Table 31). Other points to note are:

(1) An assessment of the relationship between the average annual ambient temperature and SOC storage in cotton fields suggests an optimum temperature range of 25.4 °C in Central New South Wales to 30.1 °C for Central Queensland for maximum SOC storage (Hulugalle, 2013). The changing climate and the current trend of higher than average summer temperatures may alter this relationship and long-term monitoring of SOC is essential to better understand the mechanisms and potential for SOC sequestration.

(2) Management practices approved for Bollgard III™ GM cotton varieties permit growers to avoid the mandatory post-harvest soil disturbance if the first crop defoliation has been applied before 31st March. This can potentially further minimize tillage operations.

Table 31. Soil organic carbon storage potential from field experiments in Australian cotton farming systems

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Australia (NW NSW*)	Warm temperate dry	Grumic, sodic Vertisol (Pellic)	61.8	0.75	5 (2002-2007)	0-60	Irrigated. Minimum tillage with *in-situ* stubble retention; values are average of cotton monoculture, cotton-wheat, cotton-vetch and cotton-wheat-vetch rotations (Photo 14 and Photo 15).	Hulugalle *et al.* (2014); Hulugalle *et al.* (2013)
				2.59	6 (2007-2013)			
			54.7	-1.58	9 (2000-2009)	0-60	Irrigated with treated sewage effluent. Minimum tillage with *in-situ* stubble retention; cotton wheat rotation.	
				3.91	4 (2009-2013)			
			89.2	-4.67	6 (1993-1999)	0-60	Irrigated. 1993-1999: Reduced tillage; values are average of cotton monoculture, long-fallow cotton, cotton-wheat or cotton-legume rotations. Irrigated with sodic/moderately saline bore water. 1999-2004: Reduced tillage, cotton-wheat-sorghum-fallow rotation. Irrigated with good quality river water	Hulugalle and Scott (2008)
				2.10	5 (1999-2004)			

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
		Grumic Vertisol (Humic)	39.4	0.28	10 (1998-2008)	0-30	Irrigated. Minimum tillage; values are average of cotton wheat and cotton legume rotations. Groundcover present during fallow.	Rochester, Peoples and Constable (2011)
Australia (CW NSW**)	Warm temperate dry	Grumic, Vertisol (Pellic)	83.8	-5.24	5 (1993-1998)	0-60	Irrigated. 1993-1998: Minimum tillage; values are average of cotton monoculture, long-fallow cotton, cotton-wheat or cotton-legume rotations. 1998-2009: Minimum tillage and cotton-wheat rotation	Hulugalle *et al.* (2014); Hulugalle and Scott (2008)
				0.04	11 (1998-2009)			
Australia (NW NSW*)	Warm temperate dry	Grumic, Vertisol (Pellic)	95.0	-1.07	20 (1993-2013)	0-60	Irrigated; conventional tillage/ cotton monoculture***	Hulugalle *et al.* (2014); Hulugalle and Scott (2008)
			97.0	-1.01	20 (1993-2013)	0-60	Irrigated; minimum tillage/ cotton monoculture***	
			99.0	-0.92	20 (1993-2013)	0-60	Irrigated; minimum tillage/ cotton-wheat rotation; 1993-1999: wheat stubble incorporated, 2000-2013: wheat stubble retained *in situ****	

*North-west NSW (Namoi Valley); **Central-west NSW (Macquarie Valley); ***experiment was established during 1985, but SOC measurements did not commence until 1993; regular laser-levelling and bed alignment occurred between 2003 and 2011

6. Other benefits of the practice

6.1. Improvement of soil properties

Minimum tillage reduced the rate of SOC decline (Hulugalle *et al.,* 2014), primarily through a process of maintaining soil structural stability and porosity due to reduced soil inversion, compaction and smearing associated with more intensive tillage operations. However, in Australian cotton systems the mandatory post-harvest soil disturbance of the surface 10 cm to destroy *Heliothis* moth pupae may negate such benefits. Crop rotation modifies soil properties and benefits subsequent cotton production, although the relative benefits of cereal and legume crops differ. Cereals such as wheat improve soil structure due to more intense wetting and drying cycles compared with cotton or legumes. Improved soil porosity and structural stability are reliant upon frequent wetting and drying cycles in soils with swelling and shrinking nature (Vertisols). The capacity of a wheat crop to dry the subsoil is related to its greater and more fibrous root density at depth (Hulugalle and Scott, 2008). Greater infiltrability of soil under maize was due to an interaction with the preceding wheat rotation (Nachimuthu *et al.,* 2018).

6.2 Minimization of threats to soil functions

Table 32. Soil threats

Soil threats	
Soil erosion	Australian Cotton farms use a closed irrigation network that minimizes the off-farm movement of soils, sediments and solutes during irrigation and storm events (except major flooding). Eroded soil is captured within the irrigation tail drains and channels which are subsequently desilted and reapplied on farm (Nachimuthu and Webb, 2016). Laser-levelling of paddocks to improve surface water flow and reduce waterlogging will reduce nitrous oxide emissions associated with denitrification. Dissolved and particulate carbon transported in irrigation water adds 0.02–0.2 tC/ha/yr to SOC stocks (Nachimuthu *et al.*, 2018).
Nutrient imbalance and cycles	Cotton growers no longer rake and burn cotton stubble post-harvest (Smith and Welsh, 2018). Instead, mechanized mulching of stubble recycles nutrients into the soil (Photo 17). The long-term decline of SOC with cotton monoculture (Hulugalle *et al.,* 2020) is likely to lead to a decline in the soil organic N pool. A comparison of irrigated and dryland Vertisols (McLeod *et al.*, 2013) found less total N in the 0–10 cm of irrigated soils than in minimum-till dryland soils, but irrigated soils had a lower C:N ratio (more total N stored at same level of C).

Soil threats	
Soil salinization and alkalinization	Soil electrical conductivity (EC) was higher in the 0–30 cm of surveyed irrigated Vertisols than in dryland Vertisols (McLeod et al., 2013), reflecting the salt input in irrigation water.
Soil acidification	Singh, Odeh and McBratney (2003) indicated that soil pH will drop by 1 unit within 100 years for 90 percent of cotton soils and within 15 years for 10 percent of the soils. However, more research is needed to investigate the counter-effects of water fluxes and carbonate dissolution on buffering these potential changes.
Soil biodiversity loss	Minimum tillage, when combined with wheat rotation crops, improved the numbers of indicator species such as ants and springtails (Hulugalle, Lobry de Bruyn and Entwistle, 1997). Application of fertilizer to the rotation crops reduced soil fauna numbers due to increased ground cover reducing soil temperatures (N'Kem *et al.*, 2002). Wolf spider (a predator of Heliothis moths) species were more abundant in more complex crop rotations sown with minimum tillage (Rendon *et al.,* 2015).
Soil compaction	Cotton-cereal rotation and minimum tillage alleviated soil compaction. The fibrous cereal root systems facilitated more intensive wetting/drying, which in turn improved soil structure in Vertisols (Hulugalle and Scott, 2008; Hulugalle *et al.,* 2017). The cereal crops further improved structure by creating root channels in the subsoil (Hulugalle, Lobry de Bruyn and Entwistle, 1997). Cotton-cereal rotation with in situ stubble retention reduced surface soil crusting and improved surface soil structure compared with cotton monoculture.
Soil water management	Cotton-wheat rotation with minimum tillage enhanced soil water storage compared with cotton monoculture (Hulugalle *et al.*, 2010). Cropping systems that included rotation crops generated higher returns per unit of water applied (Hulugalle and Scott, 2008; Nachimuthu *et al.*, 2017). During flooding, better drainage in minimum-tilled wheat rotation fields (Hulugalle *et al.*, 2010) enabled cotton to make a rapid recovery in comparison with conventional tillage (Photo 18).

6.3 On provision services (e.g. food/fuel/feed/timber/fibre)

Average cotton yield per hectare in Australia is the highest in the world (2.5–3 times higher than the global average). Equivalent levels of cotton production in other parts of the world require three times the area of land used in Australia, along with greater associated off-farm impacts of production. The highly fertile Vertisols, along with modern cultivars of high yield potential, maximize the resource-use efficiency of Australian cotton production. Adopting minimum tillage further reduces the off-farm impact and improves the environmental footprint of Australian cotton production.

6.4 Mitigation of and adaptation to climate change

Nitrous oxide (N_2O) is the main concern for irrigated cotton in Australia among the three greenhouse gases contributing to global warming (carbon dioxide, methane and nitrous oxide). Irrigated cotton grown on alkaline Vertisols often uses nitrogen (N) fertilizer inefficiently, largely due to denitrification losses of N_2O and dinitrogen (N_2). Grace *et al.* (2016) found that the influence of N fertilizer rate on measured Australian N_2O emissions data was best described by a two-component model that was linear in the range of crop N requirement but increased exponentially at higher N rates. The Australian N_2O emission factor (EF) is very low (0.58 percent) at the likely maximum crop N requirement of 250 kg N/ha. However, the EF rapidly increases at higher N application rates, reaching 3.32 percent at the highest observed N input level of 320 kg N/ha (Grace *et al.,* 2016). Current industry surveys indicate N application rates average 330 kg N/ha, so N_2O emissions can be mitigated by reduced N fertilizer rates without reducing yields. Rotating cotton crops with N_2-fixing legumes can substantially reduce the required N rate (Rochester, Peoples and Constable, 2001).

N_2O emissions may be reduced by managing, reducing, or avoiding denitrification. The use of nitrification inhibitors at the time of application of pre-plant N fertilizer maintains N as ammonium for several months, thereby avoiding loss of nitrate-N via denitrification (Rochester, 2003; Rochester and Constable, 2000). In a study using pre-plant anhydrous ammonia injected into the soil, Schwenke and McPherson (2018) reduced N_2O emissions by 65–86 percent over the first two months after application using nitrification inhibitors, compared with untreated anhydrous ammonia. Most N_2O emissions occur in the first few months of the cotton growing season (Macdonald, Rochester and Nadelko, 2015; Schwenke and McPherson, 2018), unless the crop receives in-crop N fertilizer followed by irrigation or rainfall (Schwenke *et al.,* 2020). Since there is little crop N use during the plant establishment phase, seasonal N_2O emissions should be reduced by applying more N fertilizer in-crop rather than all pre-planting (standard industry practice until recently). Many growers now apply N fertilizer in-crop, band either side of plant row in soil, broadcast onto the surface, or as fertigation. However, Schwenke and McPherson (2020) found splitting N fertilizer between pre-sowing and in-season applications did not impact cumulative seasonal N_2O emissions at one site and slightly increased overall N_2O loss at another. In the same study, altering pre-plant N fertilizer placement in relation to the irrigated furrow location changed the intensity of N_2O emissions, but the not the overall cumulative N_2O losses.

6.5 Socio-economic benefits

The socio-economic benefits of minimizing tillage include less production cost and energy use. Climate change is likely to increase the frequency of droughts in Australia. Where irrigation water, rather than land, is the limiting resource, cotton-wheat systems under minimum tillage would be more profitable than cotton monoculture (Hulugalle and Scott, 2008; Nachimuthu *et al.,* 2017).

N fertilizer cost savings and associated environmental benefits in irrigated cotton (Welsh, Powell and Scott, 2015) are possible by: 1) matching the N fertilizer application to meet the crop demand, 2) use of legume crops to reduce N fertilizer rate required, and 3) use of nitrification inhibitor to reduce N rate required for optimum production (cost benefit analysis warrants further work).

6.6 Other benefits of the practice

Approximately 75 percent of Australian cotton growers participate in myBMP, a voluntary program which provides self-assessment tools, mechanisms and auditing processes to ensure cotton is produced according to best management practices.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 33. Soil threats

Soil threats	
Soil erosion	Cotton farms are periodically laser levelled to improve the hydrology (infiltration/drainage) of the cotton fields. However, this may enhance soil erosion, losses of beneficial mycorrhiza and increase compaction.
Nutrient imbalance and cycles	Application of N fertilizer at rates above crop requirements can lead to exponential increases in GHG emissions, specifically N_2O. Deep banding of N to minimize N losses in runoff can lead to higher soil disturbance.
Soil salinization and alkalinization	Legume crops are sensitive to soil salinity and sodicity, and may only offer limited soil benefits whereas, wheat rotation under minimum tillage is better suited under these conditions (Hulugalle and Scott, 2008)
Soil sealing	Tillage can remove soil sealing after rainfall impact and enhance seedling establishment but may cause compaction and smearing.
Soil compaction	Cotton monoculture and cotton-wheat rotation with long fallow resulted in less compaction than cropping systems that minimize fallow with cereal or legume rotation (cotton-wheat-vetch and cotton-vetch). Higher compaction in the rotation systems may be due to management practices associated with the vetch component (Hulugalle *et al.*, 2017).
Soil water management	Water is a scarce commodity in Australia and not always available to farmers if supply dams are low. The water price is increasing every year. The conservation of water needed to grow cotton might limit growers from adopting a cover crop rotation (Photo 16) as there is no obvious economic incentive for the water used.

7.2 Increases in greenhouse gas emissions

A life-cycle analysis (LCA) showed that minimum tillage when combined with wheat rotation crops can reduce greenhouse gas emissions in comparison with minimum-tilled or conventionally tilled cotton monoculture (**Figure 11**). Among all cropping systems, the major contributors to greenhouse gas emissions were field operations (58 percent), N fertilizer production (21 percent) and N_2O emissions from soil (36 percent). Within field operations, the major contributors to emissions were irrigation (65 percent), land preparation (16 percent) and harvesting/picking (13 percent). Average kg of CO_2eq emitted per kg of cotton lint produced were 1.3 with conventional-tilled cotton monoculture, 1.2 with minimum-tilled cotton monoculture, and 0.8 with minimum-tilled cotton-wheat. Similar to emissions per unit area, emissions associated with producing a kg of cotton lint was least with minimum-tilled cotton-wheat.

A full LCA approach (Hedayati *et al.* 2019) that utilized locally derived N_2O emission factors in its calculations (Grace *et al.,* 2016) estimated potential GHG mitigative benefits of reducing N fertilizer rate from a commercial rate of 255 kg N/ha to 240 kg N/ha or 180 kg N/ha (2.6 percent and 13.2 percent emissions reduction); use of controlled-release and stabilized N fertilizers (5.9 percent reduction), changing from diesel to solar-powered irrigation pumps (8.1 percent reduction), changing from diesel to biofuel-powered farm machinery (3.4 percent reduction), changing from continuous cotton to a cotton-legume crop rotation (3.9 percent reduction) and use of N fertigation (2.1 percent reduction). The above calculations assumed that SOC had reached a steady state, although it was not clear whether the reduction in N_2O losses was offset by the reduction in SOC sequestration during lower-biomass legume crops.

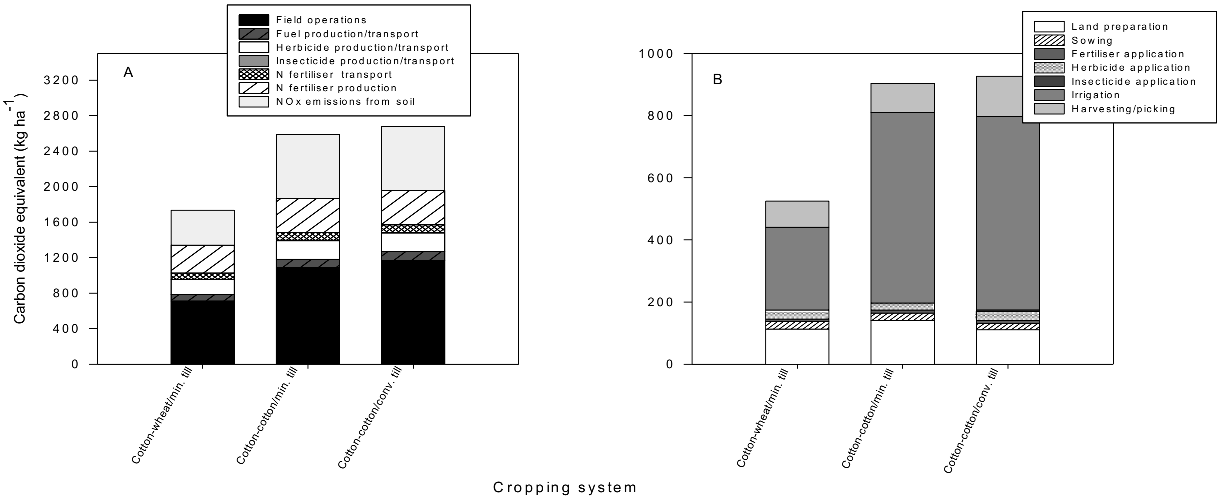

Figure 11. Effect of cropping system on average greenhouse gas emissions (2011-2017)

This is expressed as carbon dioxide equivalents (kg/ha) associated with various inputs and farming operations. Adapted from Hulugalle *et al.* 2020

7.3 Conflict with other practice(s)

Application of urea or urea ammonium nitrate (UAN) via fertigation is an increasingly popular practice for many cotton growers for applying in-crop N fertilizer. Compared with in-crop side-dressing or topdressing with tractor-based equipment, fertigation minimizes additional machinery traffic within cotton fields, and therefore may reduce soil compaction with its concomitant effects on yield.

7.4 Decreases in production (food/fuel/feed/timber/fibre)

Adoption of minimum tillage requires additional herbicide usage to manage weeds, particularly as current cotton varieties are “roundup ready” and therefore volunteer cotton plants cannot be controlled using glyphosate. Instead, control of volunteer cotton may require strategic tillage or manual weeding to maintain productivity. This may increase production cost and also be detrimental to soil structure.

7.5 Other conflicts

The adoption of the round bale module six-row cotton picker in Australia to minimize wheel traffic, labour and energy costs has been shown to increase deep soil compaction due to its weight (>30 t), compared to the previous standard of four-row pickers (Braunack, Bange and Bennett, 2017).

8. Recommendations before implementing the practice

The different barriers listed below (section 8) and management practices are inter-related and increase the challenges to improve SOC sequestration potential in Australian cotton farming systems. For example, the economic barrier (cost of irrigation water) and the natural resource barrier (water use on cotton farm) are interrelated. The lack of incentives for a minimum improvement in SOC is an institutional barrier under current Australian carbon farming methodology.

9. Potential barriers for adoption

Table 34. Potential barriers to adoption

Barrier	YES/NO	
Biophysical/ Natural resource	Yes	Water availability can be a barrier to improving SOC in cotton farming systems of Australia (Hulugalle *et al.*, 2014). Deep soil compaction may require ameliorative tillage (Braunack *et al.*, 2017).
Cultural / Social	Yes	Historically, intensive tillage was common (McGarry, 1995). Through force of habit, this may be difficult for some growers to avoid. Some older generation growers undertake multiple tillage operations.
Economic	Yes	Water is a scarce and expensive commodity for crop production in Australia. Its potential use is limited by availability and buying capacity of the cotton grower. Surface mulching and subsequent planting of cotton require specialized equipment. This may lead to additional production costs.
Institutional	Yes	The current carbon farming initiative in Australia warrants 2000 t of CO2-e abatement as a minimum for participation in the emission reduction fund program (Powell *et al.*, 2020). This level of abatement requires a large area of land and there are practical limitations (e.g. overall farm sizes) to achieving this level of emission reduction. A change in regulation that encourages a more incremental improvement in SOC has the potential to provide soil health and environmental benefits.
Other	Yes	Soil disturbance (post-harvest shallow tillage) is mandatory for GM cotton and limits the opportunities for growers to minimise tillage. The current Bollgard III™ technology allows growers to avoid pupae busting if the first crop defoliation is completed before March 31st, but this may not be practical if the seasonal conditions do not lead to crop maturity before this date (Photo 19).

Photos

Photo 14. Vetch growing in wheat stubble; Wheat was sown after cotton

Photo 15. Vetch crop mulched before cotton planting (Spring 2016)

Photo 16. Cotton growing in oat Stubble

Photo 17. Cotton stubble mulching (post-harvest)

Photo 18. Cotton growth after flooding

Minimum-tilled cotton-wheat plots in the background; conventional-tilled cotton monoculture in foreground.

Photo 19. Under the approved practices for Bollgard III™ GM cotton, growers may avoid the post-harvest soil disturbance

This, if the 1st defoliation occurs before 31st March. This can potentially further minimise tillage operations.

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9. Grazing management in rangeland grassland systems in South and East Australia

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1. Related practices

Grazing management (rotational grazing)

2. Description of the case study

Rotational grazing (i.e. a system where livestock are moved to portions of the pasture (called paddocks) while the other portions rest) has become widely applied across South and East Australia, mostly in the state of New South Wales (NSW). This is replacing traditional forms of grazing such as continuous grazing because of its potential to enhance SOC densities/stocks in grasslands, and conserve ecosystem sustainability, as well as promote production outcomes (McDonald *et al.*, 2019). Controlling animal stocking, intensity and duration can result in a more favourable environment for plant growth, and organic matter allocation to soil by improving soil hydraulic conductivity and infiltration through reducing the bulk density and compaction (Orgill *et al.*, 2018).

Overall, rotational grazing is considered as an effective carbon management strategy with additional benefits and is regarded as a contributor to the protection of the natural environment improving resilience to the impacts of climate change (Conant *et al.*, 2017). In Australia, this form of grazing management has been used in combination with others such as partial exclusion fencing to reduce native and feral animal populations (Waters *et al.*, 2017). Despite the general benefits of this grazing management strategy, its potential for carbon sequestration can vary across soil types, locations, and environmental factors (Orgill *et al.*, 2017; Sanderman *et al.*, 2015).

3. Context of the case study

In Australia, more than 75 percent of the total surface is defined as rangelands that extend across low rainfall and variable climatic zones including arid, semi-arid, and some seasonally high rainfall areas. Rangelands contribute significantly to Australia's economy (National Land and Water Resources Audit, 2001). These areas occupy a broad range of vegetation types from tropical woodlands to shrublands, grasslands and saltbush. Soils in these areas, with low nutrient contents and varying deficiencies of nitrogen and phosphorus and trace elements, are typically Vertisols and Durasols. Overall, soils in Australian rangelands are typically lower in contents of SOC compared with other areas (e.g. the United States of America), because of contrasting differences in soil type and climate (Badgery *et al.*, 2017). Mean annual rainfall ranges typically between 300 and 800 mm and mean annual maximum temperatures can be in the range of 20-23°C and the minimum temperatures between 6 and 10.5 ° C (Chan *et al.*, 2010).

Arid and semi-arid tropical areas in Australia are used for extensive cattle grazing. In the intermediate rainfall areas such as most of the Eastern and Southern Australia (which extends from southeastern Queensland through New South Wales, northern Victoria and southern South Australia), grazing management is often used to maintain pastures in an optimal composition and productive state, and to adjust the quality and quantity of forage required for grazing animals (Badgery *et al.*, 2017). Nevertheless, the appropriate intensity and management of grazing is still questioned and depends on several factors (Orgill *et al.*, 2017). Rotational grazing is now broadly considered as an effective and sustainable grazing management practice in Australian grasslands (Orgill *et al.*, 2018; Sanderman *et al.*, 2015), sometimes in combination with other approaches, e.g. improved pasture, fertilization, exclusion or use of native grasses (McDonald *et al.*, 2019).

4. Possibility of scaling up

Rangeland management through rotational grazing is applied in several areas worldwide but there are different benefits and constraints for adopting this practice that are specific to each country or region. In the United States of America, many grassland ecosystems are threatened by long-term overgrazing, increasingly frequent and severe drought, and land use change (Teague, 2018). The most common form of grazing management on rangeland and pasture in the Great Plains of the United States of America has been continuous year-round stocking. This management has had several negative consequences including reduced productivity and decreased soil carbon. Recent studies propose rotational grazing in these areas as an effective method for increasing efficiency in forage utilization and promoting soils C sequestration as a carbon mitigation option (Wang *et al.*, 2015).

In other areas such as China, livestock grazing is the dominant form of grassland use. To meet food demands and economic development, intense forms of grazing such as continuous grazing have been the most frequently applied. Because of increased degradation in grasslands, policies regulating grazing were implemented at the end of the 90's and some farms have since then established grazing management practices such as seasonal or rotational grazing (Dong *et al.*, 2020). Other areas with large potential for broad implementation of sustainable grazing management are Europe where moderate grazing can contribute to maintaining protected plant communities and at the same time reducing fuel loads and wildfire hazard (Silva *et al.*, 2019). Also, in Eastern Africa, where 75 percent of the surface is dominated by managed grassland systems, there is a yet untapped potential for C sequestration with managed grazing (Tessema *et al.*, 2020).

5. Impact on soil organic carbon stocks

There is a large variation in the results of the impacts of grazing on SOC densities/stocks, generally as a consequence of the interactions between climate, edaphic factors including initial SOC levels, and management variability (Orgill *et al.*, 2017; Waters *et al.*, 2017; Table 35). However, lower sequestration rates were reported on average for Australia (0.09 C/ha/yr) compared to other regions like Africa (0.21 tC/ha/yr) or South America (0.69 tC/ha/yr) following rotational grazing management practices.

Table 35. Carbon stock changes at 0-30 cm depth in different study locations in New South Wales (NSW), Australia

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	More information	Reference
South Eastern NSW	Warm Temperate Dry	Lixisol	29.5	1.46	4	Grazing and rest for 4-6 weeks	Orgill *et al.* (2018)
			32.9	0.78		Heavily grazed and then rested for 80-120 days	
South NSW		NA	39.2	0.41	5-10	Rotationally grazed; pair-site approach contrasted with continuous grazing	Chan *et al.* (2010)
Western NSW	Tropical Dry	Kandosols and Rudosols	21.62	1.04	8	Rotational grazing (rotational grazing + TGP fence); contrasted with continuous grazing.	Orgill *et al.* (2017)
		Kandosol	-	0.13			

6. Other benefits of the practice

6.1. Improvement of soil properties

Some of the additional benefits of rotational grazing are the reduction of and protection against soil erosion, enhancement of the aboveground diversity and productivity and increased microbial activity (Dong *et al.*, 2020). With this practice, plants are grazed in their vegetative state for relatively short periods, compared with continuous grazing, diminishing the tendency for preferred species to be grazed. Also, the rest periods allow perennials to replenish their root reserves and better tolerate dry periods, promoting both soil structure and land condition (Waters *et al.*, 2017).

6.2 Minimization of threats to soil functions

Table 36. Soil threats

Soil threats	
Soil erosion	Larger groundcover promotes soil protection from erosion (Orgill *et al.*, 2017).
Nutrient imbalance and cycles	Through enhanced plant productivity, nutrient cycling, and diversity (Waters *et al.*, 2017).
Soil contamination / pollution	Reduction or replacement of mineral and fertilizers (Orgill *et al.*, 2018; Waters *et al.*, 2017).
Soil biodiversity loss	Enhanced plant diversity (McDonald *et al.*, 2019; Waters *et al.*, 2017).
Soil compaction	Reduced bulk density and compaction (Chan *et al.*, 2010; Orgill *et al.*, 2018).
Soil water management	Improved soil hydraulic conductivity and infiltration (Orgill *et al.*, 2018).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Management of grazing through rotational or low-intensity grazing can affect both above and below-ground biomass production as well as ground cover. In Eastern and Southern Australia, there has been evidence that exclusion fencing (and thus reduction of grazing pressure) can result in higher perennial and litter ground cover (Waters *et al.*, 2017). Both perennial grasses and litter form are an important source of organic matter in Australian rangelands through food provision and shelter for organisms. In addition, trees can provide shading and shelter for livestock (Orgill *et al.*, 2017).

6.4 Mitigation of and adaptation to climate change

Predictions in Australian rangelands estimate indicate that continuous grazing combined with long-term patterns of drought can result in emissions of 730 to 1 470 Mt CO_2eq in any 5-year period (Hill *et al.*, 2006). More sustainable grazing land management practices could offer opportunities for reducing GHG emissions from rangelands and savannas in Australia. For example, in regions of South Australia, it has been reported that the recovery of chenopod shrubland by grazing management can recue GHG fluxes between 0.1 and 0.6 t CO_2eq/ha/yr (Henry, Butler and Wiedemann, 2015).

6.5 Socio-economic benefits

Other benefits of rotational grazing include even grazing pressure and reduced herbivore selectivity and selection of palatable species; enhanced flowering, growth and survival of plant species; improved pasture utilization and maintenance of pasture cover; higher perennial grass content; and increased herbage production and animal production (Badgery *et al.*, 2018; Sanderman *et al.*, 2015).

7. Potential drawbacks to the practice

Rotational grazing can increase the need for infrastructure and labour and may not be practical when plants are not growing, sheep and cattle are lambing and/or calving (Wang *et al.*, 2020). The reduced opportunity to selectively graze following a rotational grazing management approach can also lead to a decline in production due to livestock being forced to graze less nutritious plant species.

Several factors need to be considered when implementing rotational vs. continuous grazing management such as baseline SOC concentrations, topography, climate, vegetation, and soil types, as shown in previous studies that have reported a large variation in SOC sequestration as a consequence of these factors (Khalil *et al.*, 2007; Orgill *et al.*, 2017). Moreover, some mechanistic processes including primary productivity and species composition, allocation of nutrients between roots and shoot, stocking density, and modifications in the decomposition and carbon export through processes at landscape levels can also influence the effects of grazing activity on carbon cycling (Allen *et al.*, 2014). Grazing may also not influence nutrients like N and additional incorporation may need to be considered (Orgill *et al.*, 2017). Besides, the biomass remaining in the fields at the end of the grazing season determines the maximum stocking density allowed for a good pasture management. So, the stocking density must not exceed the grassland carrying capacity.

8. Potential barriers for adoption

Table 37. Potential barriers to adoption

Barrier	YES/NO	
Social	Yes	Potential increased amount of labour required for management intensification; uncertainties in investment (e.g. fencing repairs; water points installation); potential decline in forage quality if pastures are not harvested in a timely manner.
Economic	Yes	
Legal (Right to soil)	Yes	Lease agreement may be designed exclusively for conventional grazing.

Barrier	YES/NO	
Knowledge	Yes	Lack of information about the benefit of the practices
Natural resource	Yes	Weather/climate factors may be challenging, e.g. drought periods.

Source: Wang et al. (2020)

Photo

Photo 20. Northern tablelands of New South Wales (Eastern Australia) 2012

Foreground is grazed only by native macropods with main paddock lightly grazed by sheep.

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10. 16 years of no tillage and residue cover on continuous maize in a Black soil of China

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1. Related practices and hot-spot

No-tillage, Organic mulch; black soil

2. Description of the case study

Northeast China is a key area of commercial grain production in China, and thus plays a crucial role in China′s food security (Yang *et al.*, 2007; Liang *et al.*, 2009). However, in recent years, substantial losses of soil organic carbon (SOC) have been observed, which has resulted in a significant reduction in soil fertility (Xu *et al.,* 2010; Zhou *et al.,* 2018). This phenomenon has been aggravated by conventional tillage (CT) practice which included removal of crop residue after harvest and moldboard plowing (Zhang *et al.,* 2015). This type of practice has caused the decline of SOC, degradation of soil structure and extensive wind and water erosion (Liu *et al.*, 2010). Conservation tillage, particularly no tillage (NT), has been suggested to be an effective practice to control soil erosion and increase the SOC content in Northeast China (Zhang *et al.*, 2007, Liang *et al.*, 2016). Based on a long-term tillage experiment established in 2001, researches on the influences of NT on soil physical properties (bulk density, aggregation, water infiltration, soil structure) (Chen *et al.*, 2014, 2018), chemical components (SOC, soil nitrogen cycle and other nutrients) (Li *et al.,* 2011; Liang *et al.*, 2016; Zhang *et al.,* 2018, 2019, 2020; Liu *et al.*, 2017) and microbial community (Zhang *et al.*, 2012, 2016; Jia *et al.*, 2016; Sun *et al.*, 2016 and 2020; Liang *et al.*, 2019) had been done and more than 100 papers had been published in international or Chinese journals.

3. Context of the case study

The field experiment was established in the Experimental Station (44°12′N, 125°33′E) of Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, in Dehui County, Jilin Province, China in fall 2001. The experimental site is located in North Temperate Zone and has a continental monsoon climate. The coldest month is in January (−19.5°C) and the warmest month is in July (24.5°C) and the mean annual temperature is 4.4°C. The mean annual precipitation is 520 mm with > 70% occurring during the growing season from June to August (Liang *et al.,* 2007). The clay loam soil is classified as Typic Hapludoll according to the USDA Soil Taxonomy.

4. Possibility of scaling up

The case study can be adapted for scaling up to the clay loam under continental monsoon climate.

5. Impact on soil organic carbon stocks

Returning residue to the soil significantly increased SOC storage after 16 years, no tillage with continuous maize having the highest increase in rate of SOC storage at 0.80 tC/ha/yr relative to the start of the experiment in 2001 in 0-30 cm layer (Table 38).

Table 38. Evolution of SOC stocks at the study site on 0-30 cm in the 16-year study

Location	Soil type	Baseline stock (tC/ha)	C seq potential (tC/ha/yr)*	Duration (Years)	Reference
Northeast China	Mollisol	63.8	0.80 ± 0.05	16	Zhang *et al.* (2018)

*Data are presented as average ± SE of four replicates

6. Other benefits of the practice

6.1. Improvement of soil properties

Bulk density: NT (1.15 g/cm^3 in 0-5 cm layer) led to significant bulk density increment over that of CT (1.01 g/cm^3 in 0-5 cm layer), but it was still lower than the range where root elongation becomes severely restricted (Chen *et al.*, 2014).

Aggregate stability: NT improved the aggregate stability compared to CT. Microbial biomass and glomalin were the most important driving factors for aggregate stability in the NT systems (Zhang *et al.*, 2012).

Water infiltration: Higher water infiltration rates occurred in NT (5.2 mm/min) than in CT (2.5 mm/min) soils, which was affected by the earthworm quantities (Chen *et al.*, 2018).

Soil penetration resistance: Compared with CT, NT increased soil penetration resistance at the depths of 2.5-17.5 cm (Chen *et al.*, 2014).

Nutrient content: NT resulted in the obvious accumulation of SOC, TN, available N, P and K on soil surface (Li *et al.*, 2011).

Soil macroporosity: NT (11.78% in 0-5 cm layer) showed a significantly lower soil macroporosity than CT (12.81% in 0-5 cm layer) due to less disturbance (Chen *et al.*, 2014).

6.2 Minimization of threats to soil functions

Table 39. Soil threats

Soil threats	
Soil erosion	Over the entire growing season, NT maintained a stable soil structure, improved aggregate stability and prevented soil erosion (Chen, 2016).
Nutrient imbalance and cycles	NT increased the accumulation of TN, available N, P and K on soil surface due to the residue returned (Li *et al.*, 2011).
Soil salinization and alkalinization	NT did not profoundly affect soil chemical property parameters, such as soil pH values (Li *et al.*, 2012).
Soil acidification	NT did not profoundly affect soil chemical property parameters, such as soil pH values (Li *et al.*, 2012).
Soil biodiversity loss	NT practice has potential for improving microbial properties in surface soil, but may not cause a shift of microbial community structure (Sun *et al.*, 2016).
Soil water management	NT enhanced the soil water content of 0-10 cm layer because of the retention of crop residues on the surface and less disturbance (Chen *et al.*, 2014).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Compared with CT, NT had higher maize grain yield, soil carbon/nitrogen ratio and soil moisture, and lower soil temperature and seedling emergence rate (Zhang *et al.*, 2015).

NT (30 kg/ha) had less fuel consumption than CT (230 kg/ha) which mainly contributed to the reduction of GHGs emissions (Wei, Liang and McLaughlin, unpublished).

6.4 Mitigation of and adaptation to climate change

NT was a sink of GHG, the CO_2 eq mitigated was 1.90 t/ha/yr by NT (Huang *et al.*, 2011).

Under Typhoon condition, NT resulted in significantly lower lodging compared with CT (*Liang et al., 2017*). NT has significant yield advantages under extreme drought conditions by improving the soil water content (Zhang, 2019). Our results also suggest that NT can mitigate the effects of drought on soil functions from a holistic ecosystem view (Zhang *et al.,* 2019).

6.5 Socio-economic benefits

NT had 15.9% higher corn profitability, and 62.9% higher soybean profitability than CT (Fan *et al.*, 2012). This might be explained by the fact that legume crops had higher residue nitrogen than cereal crops, and the increased soil nitrogen content from soybean growing was one of the factors leading to higher corn yield (Gentry *et al.* 2001). The lower fuel and labor cost under NT also contributed to the high socio-economic benefits (Figure 12) (Fan *et al.*, 2012).

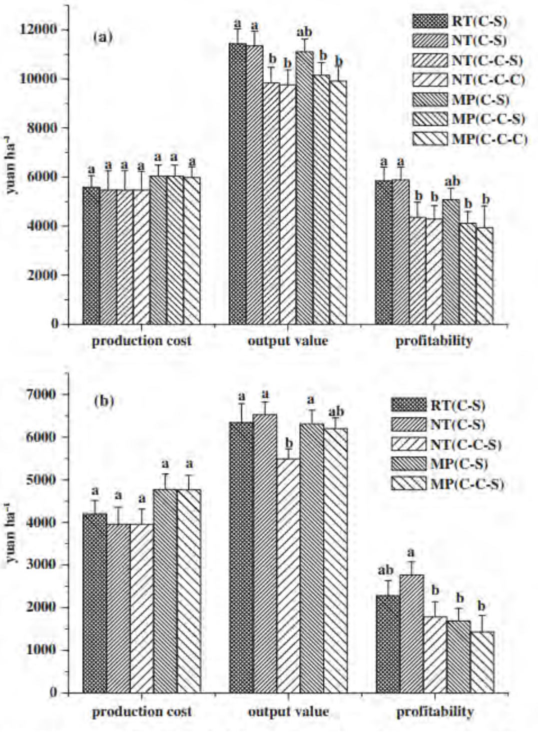

Figure 12. Mean crop production costs, output value and profitability for corn (a) and soybean (b)

(a) and (b) in different treatments from 2002 to 2009 under different tillage and rotation practices at the experimental station in Dehui County, Jilin Province, China. C = Corn, S= Soybean, RT = Ridge tillage, NT = No-till, MP = Moldboard tillage

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 40. Soil threats

Soil threats	
Soil erosion	During all the growing season, NT reduced runoff and sediment transport times, erosion modulus when compared with CT (Chen, 2016).
Nutrient imbalance and cycles	Available N, available P and available K had remarkable differences between soil surface and subsurface under NT. However, the available nutrient had no significant difference between NT and CT in the plow layer (0-30 cm) (Li *et al.*, 2011).
Soil salinization and alkalinization	Compared with CT, NT did not profoundly affect soil pH values (Li *et al.*, 2012).
Soil contamination / pollution	The autotrophic nitrification rate and the N_{aut}/I_{NH4} ratio were significantly higher in the NT top soil than in CT top soil, therefore long-term NT treatment was more likely than CT treatment to increase the risk of NO_3^- leaching and N_2O emission (Liu *et al.*, 2017), which can cause groundwater pollution.
Soil acidification	Compared with CT, NT did not profoundly affect soil pH values (Li *et al.*, 2012).
Soil biodiversity loss	NT improved microbial abundance (total, fungal and bacterial abundance) in the 0-5 cm depth soil, but it did not contribute to a higher fungal/bacterial ratio in the 0-5 cm depth soil, and had a lower fungal/bacterial ratio than CT in the deeper soils below 5 cm depth (Sun *et al.*, 2016).
Soil compaction	The bulk density and soil penetration resistance was higher in NT than CT soils due to the difference in tillage intensity (Chen *et al.*, 2014).
Soil water management	The soil water content of 0-10 cm layer was significantly higher in NT than CT soils (Chen *et al.*, 2014).

7.2 Possible greenhouse gases (GHG) emissions

The annual soil CO_2 emissions were higher under CT than under NT by 7.8% (Jia *et al.*, 2015). CT was a source of GHG in the rate of 6.0 t/ha/yr (CO_2eq) (Huang *et al.*, 2011).

7.3 Conflict with other practice(s)

When farmers make decisions about NT or CT, they consider more the short-term economic benefits than the long-term ecological and sustainability benefits. Farmers' ecological and environmental awareness has yet to be improved (Li, 2018).

7.4 Decreases in production (e.g. food/fuel/feed/timber/fibre)

Long-term NT has some constraints, for example, stratification of soil nutrients, mechanical compaction and increased weed pressure, all of which limit the adoption of NT management (Wang *et al.*, 2020). However, analysis of the results from the 12 year tillage experiment indicated that NT practice can yield higher maize grain than CT, particularly under drought conditions, by having positive effects on soil nutrients and soil water availability (Zhang *et al.*, 2015).

6.5 Other conflicts

NT requires heavier and more expensive field equipment, more attention to proper equipment adjustment, and better management than CT. It challenges traditional thinking among the local farmers.

8. Recommendations before implementing the practice

This research suggests to develop rural social education programs to improve farmers' recognition of benefits of NT technology, to strengthen the incentive mechanism for technical service entities, including improving the supply ability of NT technology services, and to optimize the support system for NT technology (Zhang *et al.*, 2020).

9. Potential barriers for adoption

Table 41. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	The CT practice had a long history (200-300 years), it requires time for farmers to accept a new technology for farmers, such as NT. The age of farmers has a significant negative impact on the adoption behavior of NT technology (Zhang *et al.*, 2020).

Barrier	YES/NO	
Social	No	The results showed that NT achieved more benefits than CT on the environmental, social and economic aspects (Li *et al.*, 2015).
Economic	No	The results showed that NT resulted in more benefits than CT on the eco-environmental, social and economic aspects (Li *et al.*, 2015).
Legal (Right to soil)	No	Adoption of NT had been listed as a priority in the soil policies and regulations2
Knowledge	No	A lot of researches had been done on NT and CT practices in China (Zhao *et al.*, 2015).
Natural resource	No	The Northeast Plain, dominated by black soils (Udolls, US Soil Taxonomy), is an important base of crop production in China. Black soil is often called "The king of soils" in China and is a very precious national land resource (Liang *et al.*, 2009).

Photo


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Photo 21. NT practice in Northeast China, Northeast Institute of Geography and Agroecology

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[2] http://www.moa.gov.cn/nybgb/2017/dqq/201801/t20180103_6133926.htm

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11. Rice straw mulching, charcoal, and no-tillage on maize in Lopburi, Thailand

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1. Related practices

No-till, Organic matter additions (rice straw mulching, rice husk charcoal application)

2. Description of the case study

Thailand has 11 million hectares of paddy fields and 4.9 million hectares of upland crop fields. Maize cultivation area was 1.1 million hectares in 2018 (Office of Agricultural Economics, 2019). In Thailand, farmers usually cultivate maize without adding organic matter, but with chemical fertilizer applications and conventional tillage. For sustainable crop production, there is a need to develop technologies to improve soil fertility. A field experiment was conducted to clarify the effects of rice straw mulching and rice husk charcoal application, as well as the implementation of no-tillage cultivation on soil properties such as soil organic carbon content from 2011 to 2015 at the Lopburi Seed Research and Development Center, Department of Agriculture (DOA), Thailand. The main crop was maize. Five treatments were carried out according to two different criteria: (1) the type of organic matter input (rice straw mulching, rice husk charcoal application, no organic matter input) and (2) tillage and no-tillage cultivation (**Error! Reference source not found.**). Chemical fertilization was applied to the treatments and the maize stover was returned to the soil.

Table 42. Different treatments at the study plot between 2011 to 2015

Treatment ID	Organic matter input	Tillage
NoT	No organic matter application	Tillage cultivation
NoNT	No organic matter application	No-tillage cultivation
RST	Rice straw mulching (3.1 t dry matter/ha/yr)	Tillage cultivation
RSNT	Rice straw mulching (3.1 t dry matter/ha/yr)	No-tillage cultivation
RHCT	Rice husk charcoal application (3.1 t dry matter/ha/yr)	Tillage cultivation
RHCNT	Rice husk charcoal application (3.1 t dry matter/ha/yr)	No-tillage cultivation

3. Context of the case study

The study was conducted in the uplands of Lopburi, Thailand, from 2011 to 2015. Soils are classified as Ultisols (USDA taxonomy) and are loamy textured. Climate at the study site is tropical savannah with a mean annual temperature of 29.4 °C and a mean annual precipitation of 1 221 mm.

4. Possibility of scaling up

In Southeast Asia, rice straw production is relatively high, as rice is one of the main crops produced in the area. Theoretically, therefore, rice straw mulching can be carried out in most of the upland crop fields. However, the application of rice husk charcoal is difficult in most of the upland crop areas, as rice husk production is not significant. No-tillage cultivation could be practiced in all regions.

5. Impact on soil organic carbon stocks

Soil samples were taken at a depth of 0-15 cm from all treatment plots before ploughing and at harvest every year from 2011 to 2015. The organic carbon content of the soil samples was analysed using the Walkley-Black method. In 2010, soil core samples were taken using a 100 mL can at 0-10 cm and 10-20 cm depth in all treatment plots, and soil bulk density was measured. SOC storage of 0-15 cm was estimated using soil organic carbon content and soil bulk density (to adjust the 0-15 cm depth, calculated as 2/3 x bulk density of 0-10 cm + 1/3 x bulk density of 10-20 cm).

The range of SOC content in all treatment plots was 6.9-8.1 gC/kg in 2011 and 7.9-10.0 gC/kg in 2015. The range of soil bulk density estimated at a depth of 0-15 cm in all treatment plot in 2010 was 1.50-1.60 g/cm^3. The SOC storage change (additional C storage potential) was estimated by linear regression using 5 years of SOC storage data.

C storage with rice straw mulching was higher than without the addition of organic matter: 0.49 and 0.40 tC/ha/yr (=0.98-0.49 and =0.98-0.58) with tillage and no-tillage respectively compared to no organic matter application. In addition, C storage with rice husk charcoal application increased by 0.22 and 0.01 (=0.71-0.49 and 0.59-0.58) tC/ha/yr under tillage and no-tillage cultivation compared to no organic matter application, respectively (Table 43).

Rice straw mulching had a better effect on C storage than rice husk charcoal application. The increase in organic carbon content of rice husk charcoal was limited (only 3 percent). The higher baseline C stock could explain the lack of increase in C storage with rice husk charcoal under no-tillage cultivation (0.01 tC/ha/yr).

No tillage cultivation increased the potential for additional C storage by 0.09 (=0.58-0.49) tC/ha/yr with no organic matter input, 0.00 (=0.98-0.98) tC/ha/yr with rice straw mulching, and -0.12 (=0.59-0.71) tC/ha/yr with rice husk charcoal, which was not significantly different between tillage and no tillage cultivation (Table 43). The reason why the increase in C storage was not different was not clarified.

Table 43. Evolution of SOC stocks at 0-15 cm between 2011 and 2015 on the study plot in Lopbri, Thailand

Treatment	Baseline C stock in 2011 (tC/ha)	Additional C storage (tC/ha/yr)
NoT	16.1 ± 1.2	0.49 ± 0.25
NoNT	16.1 ± 0.9	0.58 ± 0.17
RST	17.2 ± 0.5	0.98 ± 0.30
RSNT	19.0 ± 2.0	0.98 ± 0.84
RHCT	16.4 ± 0.6	0.71 ± 0.55
RHCNT	18.8 ± 2.1	0.59 ± 0.43

Source: Adapted from Matsumoto et al. (2020) (Submitted)

Soils are classified as Ultisols and climate is Tropical Moist, according to IPCC. The baseline C stock was measured at the beginning of the experiment in 2011, under a business as usual practice (no organic matter inputs and tillage cultivation). No, RS, RHC, T and NT refer to the different treatments detailed in **Error! Reference source not found.**. Values are provided as average of 3 values (n=3) +/- standard deviation

Rice straw mulching at 1.36 tC/ha/yr (= 3.1 t dry matter/ha/yr x 43.5 percent C content of rice straw) resulted in a significant increase in C storage of 0.49 and 0.40 tC/ha/yr in both tilled and untilled soils compared to no organic matter application for 5 years, respectively. This result shows that large amounts of C inputs increase the C content of the soil. However, a more detailed analysis of the dynamics of rice straw organic matter in the soil would be needed.

Rice husk charcoal led to lower C accumulation. However, in this case study, only soil organic C was analysed. Total C should be studied to better understand the C dynamics after rice husk application. Indeed, the existence form of charcoal (biochar) in the soil is different from that of organic matter, as it is not decomposed by soil fauna and microbials and does not change in form in the soil. An analysis of how charcoal remains in the soil is necessary.

In general, no-tillage cultivation helps to increase the carbon content of the soil by reducing the destruction of soil structure. However, in this case study, the C storage was not increased. According to our observations, soil aggregation is low in the experiment field, even in no-tillage cultivation. The dynamics of soil organic matter in no-tillage cultivation should be clarified, for example by measuring the decomposition potential of organic matter and microbial activities.

6. Other benefits of the practice

6.1. Improvement of soil properties

Exchangeable potassium (K) in the soil was higher and soil pH was slightly higher with rice straw mulching and rice husk charcoal application. However, available phosphorus, exchangeable manganese, exchangeable calcium was no different when compared to organic matter application.

Soil nitrogen content might be higher with rice straw mulching, as high C input increases the microbial biomass that absorbs available nitrogen of the soil. CEC and silica content of the soil might be higher with rice straw mulching and rice husk charcoal application, but no analysis was done.

In general, soil bulk density improved with the application of organic matter or under no-tillage cultivation. However, in this case study, soil bulk density did not improve significantly, probably because the duration of the experiment, 5 years, was too short.

Rice straw mulching increased the density and diversity of soil fauna. Part of the mesofauna feeds on decomposed rice straw and fungi on rice straw, and mesofauna predator feeds on another mesofauna. The biodiversity of some mesofauna was high under rice straw mulching, which provided habitat for the mesofauna (Kawarazaki *et al.,* 2019).

6.2 Minimization of threats to soil functions

Table 44. Soil threats

Soil threats	
Nutrient imbalance and cycles	Improving the nutrient balance of the soil with rice straw mulching and rice husk charcoal application. But, no effect on nutrient improvement with no-tillage cultivation (reason was unclear).
Soil biodiversity loss	Soil fauna increased under the rice straw mulching, as fungi, food for the soil fauna, grew on the rice straw. Soil fauna did not increase under no-tillage cultivation.
Soil water management	Rice straw mulching contributes to water retention in the soil during early maize growth, according to our observations, not measurement data. The effect of no-tillage cultivation on soil water retention is unclear.

6.3 Increases in production (e.g. food/fuel/feed/timber)

Maize grain yield increased by 8 percent with rice straw mulching and by 4 percent with rice husk charcoal application, but decreased by 6 percent with no-tillage cultivation (Figure 13).

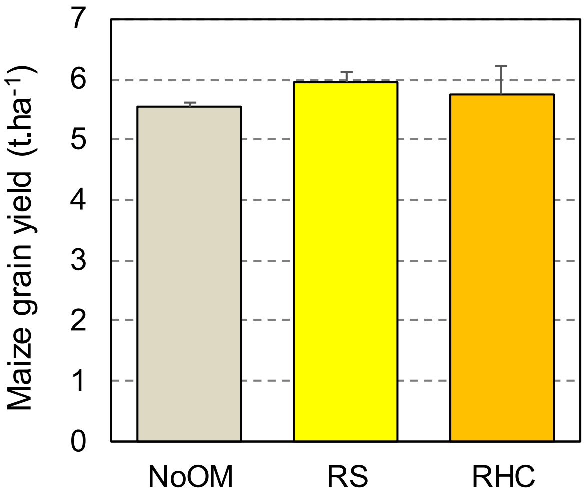

Figure 13. Maize grain yield without organic matter application (NoOM), rice straw mulching (RS), and rice husk charcoal application (RHC) in a field experiment in Thailand from 2011 to 2015

Chemical fertilizer was applied and maize stover was returned. The bar is the standard error.

6.4 Mitigation of and adaptation to climate change

The SOC increases with rice straw mulching, which contributes to the removal of CO_2 from the atmosphere. CH_4 may not be emitted in upland fields due to aerobic conditions. N_2O emissions might not be affected by organic matter input or no-tillage cultivation, because the amount of additional nitrogen was so small with organic matter input compared to chemical fertilizer application and was not different between tillage and no-tillage cultivation.

6.5 Socio-economic benefits

Economic activities will be promoted from the rice straw and rice husk charcoal supply system, such as collection, transportation, production of rice husk charcoal, manufacturing and maintenance of rice husk charcoal facility.

Also, weed management in no-tillage cultivation requires labour. As a consequence of the economic development in Thailand, various industries have emerged in which many workers are needed. The introduction of mechanization is progressing not only in the industry but also in the agricultural sector.

6.6 Other benefits of the practice

Promoting the use of rice straw contributes to the reduction of air pollution. In general, farmers burn some of the rice straw in the field to reduce insects and to prevent the rice straw from becoming entangled during plowing. Twenty percent (20 percent) of the rice straw was burnt in northeast Thailand in our 2005 survey (Matsumoto *et al.*, 2011). Gadde, Menke and Wassmann, (2009) reported that half of the rice straw was burnt. Sritoth (2007) reported that 10 percent of rice straw was burnt.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 45. Soil threats

Soil threats	
Soil contamination / pollution	Accumulation of heavy metals might occur during the supply of rice straw mulching or rice husk charcoal, when the rice absorbs heavy metals from the paddy field.

7.2 Increases in greenhouse gas emissions

When rice straw mulching and rice husk charcoal application becomes common, the collection and transportation of the rice straw and rice husk increases, requiring fuel consumption to increase GHG emissions. Rice husk charcoal production also requires fuel consumption. In addition, the production of rice husk charcoal also requires fuel consumption. Total GHG emission, including the collection and production processes, are decreasing, but attention must be paid to long distance transportation.

7.3 Conflict with other practice(s)

Rice straw is used for animal feed, so conflicts with animal feed supply must be taken into account. According to a field survey involving interviews with farmers in northeast Thailand in 2003-2005 (Matsumoto *et al.*, 2011), paddy rice farmers cut the upper rice straw to harvest the rice, and the weight of the cut upper rice straw accounted for 50 percent of the total rice straw. The upper rice straw was used 56 percent for animal feed, 32 percent for return to the paddy field, and 4 percent for burning (Figure 14). And the lower rice straw remained in the paddy field after the harvested rice was left in the paddy field (62 percent) and burnt (36 percent) (Figure 14). The amount of rice straw burned, a total of 20 percent of the rice straw, can be used for rice straw mulching in the upland crop fields. If the need for rice straw mulching by upland crop field farmers increases, there will be a conflict with the animal feed supply, or the amount of rice straw returned to the paddy field will decrease, resulting in a decrease in the organic matter content of the paddy soil. Farmer raised cattle extensively in 2003-2005, the main animal feed was rice straw, and the cattle grazed rice weeds and rice straw in the paddy field after the rice harvest. In 2020, the use of rice straw is changing, as rice is harvested using machinery and the bio-energy industry has increased, and cattle are being intensively raised using concentrated feeds, hence the need for a survey on rice straw use to clearly establish the current conditions for the use organic matter.

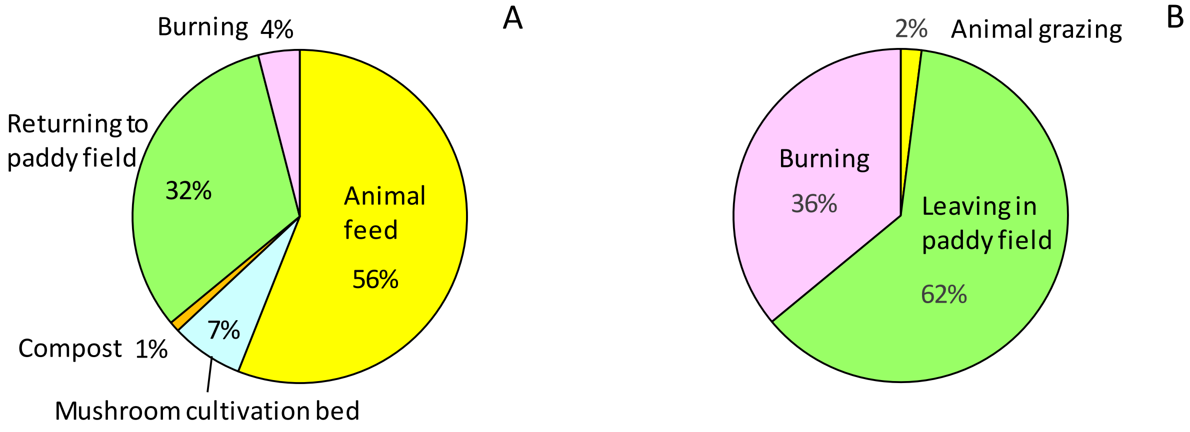

Figure 14. Use of rice straw in northeast Thailand in 2003-2005

A field survey and interviews with farmers were conducted:

A: Use of cut upper rice straw to harvest rice. B: Use of the lower rice straw left in the paddy field after rice harvest. The dry matter weight of the cut upper rice straw was 50% of the total rice straw (data from Matsumoto *et al.,* 2011).

7.4 Decreases in production (food/fuel/feed/timber/fibre)

Maize grain yield under no-tillage cultivation was 6 percent lower than it under tillage cultivation (**Figure 15**).

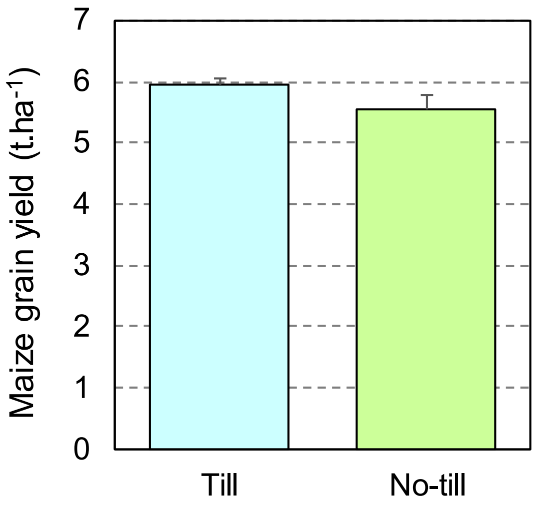

Figure 15. Maize grain yield in tilled and no-till in a field experiment in Thailand from 2011 to 2015

Chemical fertilizer was applied and maize stover was returned. The bar corresponds to the standard error.

7.5 Other conflicts

When the biomass energy industry uses rice straw and rice husk as a material, conflicts over the supply of materials should be considered.

8. Recommendations before implementing the practice

The establishment of a system for collecting, transporting, and suppling rice straw is necessary for the extension of rice straw mulching.

9. Potential barriers for adoption

Table 46. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Using rice straw for mulching on crop field is in conflict with the supply of animal feed. Promotion of pasture grass production in the area might reduce the conflict. Rice husk charcoal production is in conflict with the biomass energy industry. Even though rice husk charcoal production is not significant, the stable C in the rice husk charcoal remains in the soil and increases the storage of C in the soil.
Social	Yes	In order to spread rice straw mulching on crop fields, it is necessary to establish a rice straw supply system.
Economic	Yes	The 8 percent increase in income from maize grain yield should be greater than the cost of purchasing rice straw and mulching labor. Rice husk charcoal application is the same, the income should be higher than the cost. In no-tillage cultivation, the reduction in no-till costs should be greater than the reduction in income.
Knowledge	Yes	Rice straw mulching on maize is not familiar to farmers. Rice husk charcoal application is equally unfamiliar. An extension of the time and amount of application is needed. Extension of no-tillage cultivation is necessary, such as weed management, sowing and fertilizer application technique, etc.

Photos

Photo 22. Rice farmers harvesting rice in northeast Thailand in 2005

Farmers cut the upper rice straw with the rice grain (left). The cut upper rice straw was disposed of on or near the threshing pad in the paddy field (right).

Photo 23. Experimental field of rice straw mulching, rice husk charcoal application, and tillage and no-tillage cultivation on a maize field in Lopburi, Thailand

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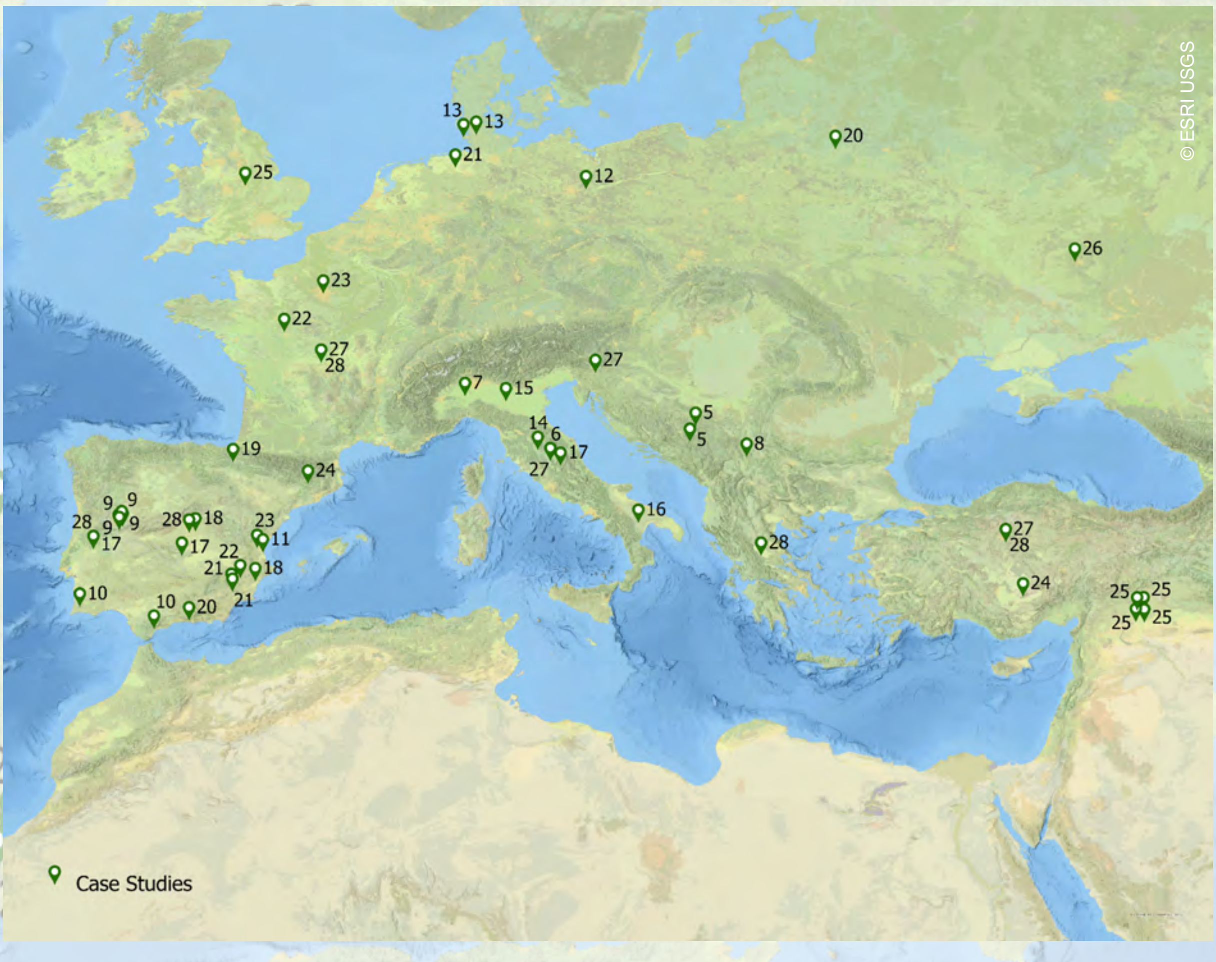
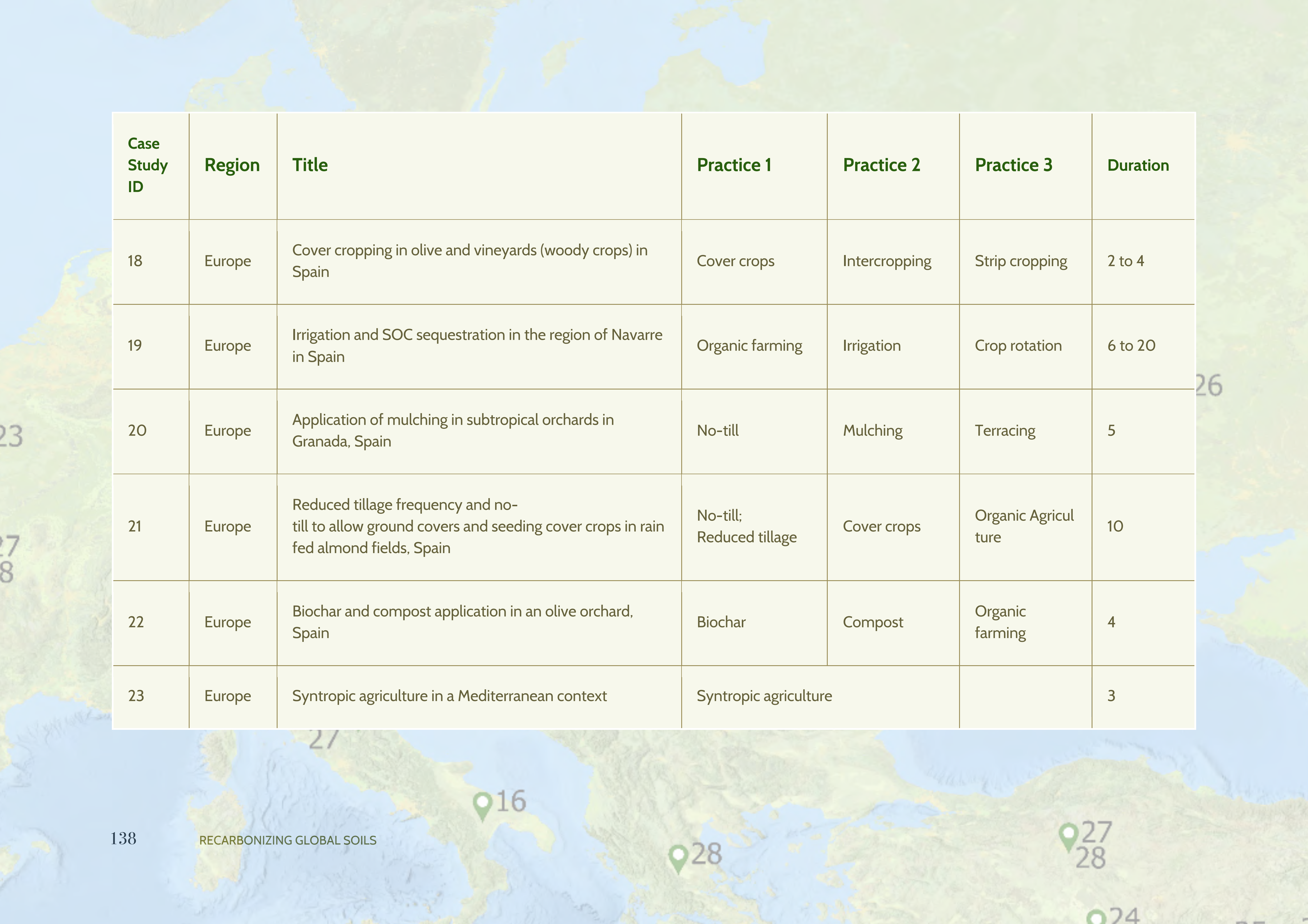
Europe and Eurasia



Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
12	Europe	Long-term experiment of manure treatments on a sandy soil, Germany	Manure	Organic fertilization	Mineral fertilization	29
13	Europe	Avoidance of land use change (LUC) from grassland to arable land, Germany	Avoided conversion of LU			1 to 7
14	Europe	The biochar challenge in viticulture: long-term experiment in Central Italy	Biochar			1 to 10
15	Europe	Conservation agriculture practices in North Italy	Conservation agriculture	Adapted irrigation		5 to 20
16	Europe	Mediterranean olive orchard subjected to sustainable management in Matera, Basilicata, Italy	Soil cover	No-till	Adapted irrigation	20
17	Europe	Mediterranean savanna-like agrosilvopastoral grassland system in Spain, Italy, and Portugal	Grassland diversification	Agrosilvopastoralism		4 to 37



Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
18	Europe	Cover cropping in olive and vineyards (woody crops) in Spain	Cover crops	Intercropping	Strip cropping	2 to 4
19	Europe	Irrigation and SOC sequestration in the region of Navarre in Spain	Organic farming	Irrigation	Crop rotation	6 to 20
20	Europe	Application of mulching in subtropical orchards in Granada, Spain	No-till	Mulching	Terracing	5
21	Europe	Reduced tillage frequency and no-till to allow ground covers and seeding cover crops in rain fed almond fields, Spain	No-till; Reduced tillage	Cover crops	Organic Agricul ture	10
22	Europe	Biochar and compost application in an olive orchard, Spain	Biochar	Compost	Organic farming	4
23	Europe	Syntropic agriculture in a Mediterranean context	Syntropic agriculture			3

Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
24	Eurasia	Pickle melon (*Cucumis melo*) production in Karapınar, Central Turkey	Manure	Mixed-farming		60
25	Eurasia	Irrigated wheat-maize-cotton in the Harran Plain, Southeast Turkey	Crop rotation	Adapted irrigation		30
26	Europe	Organo-mineral fertilization on a Ukrainian black soil	Integrated soil fertility management	Mulching		5
27	Europe	Interrow organic management to restore soil functionality of vineyards	Composting	Intercropping	Cover crops	2
28	Eurasia	Cover crops, organic amendments and combined management practices in Mediterranean woody crops	Cover crops	Organic amendments		Various (<30)

12. Long-term experiment of manure treatments on a sandy soil, Germany

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1. Related practices

Organic fertilization (Manure, straw), mineral fertilization

2. Description of the case study

The long-term field experiment "V140" (Nährstoffsteigerungsversuch) was established in 1963 at a former uniformly cultivated arable field and is today located at the Leibniz Centre for Agricultural Landscape Research (ZALF) about 50 km east of Berlin in Müncheberg. Since 1963 soil samples were taken, and analyzed for SOC and N_t. The samples taken every second year from 1982 to 1994 were archived.

The V140 represents one of the few still active long-term field experiments on sandy soils in Germany. During the running period just small management changes have been done, mostly with respect to the crop rotation and the applied fertilizer combinations and amounts. The recent research focuses mostly on the effect of fertilization on aspects of soil fertility.

The field experiment is located on a relatively flat area of a total of 5 712 m^2 which is divided in 8 replicates. Each replicate consists of 21 plots: one plot does receive neither mineral nor organic fertilizer (Control) while the other 20 plots receive fertilization consisting of 5 levels of mineral combined with 4 levels of organic fertilization (Table 47). Overall, the experiment consists of 168 plots of 5 m x 6 m size (Smukalski *et al.*, 1990) (Figure 17). Organic fertilizer was applied every second year in spring before planting sugar beet, potato, or maize, respectively. Mineral fertilizer was applied every year. More details on the soil and crop management were provided by Körschens (1990).

Table 47. Fertilizer treatments of V140, Müncheberg

Treatment	Description	Organic Fertilization	Mineral Fertilization (kg/ha)*		
		Dry mass (t/ha/yr)	*N*	*P*	*K*
0	without	0	0	7	26
1.1	NPK	0	52	30	122
1.2	NPK	0	89	35	140
1.3	NPK	0	118	38	150
1.4	NPK	0	157	43	171
1.5	NPK	0	193	48	188
2.1	NPK+FYM1	1.2	32	26	104
2.2	NPK+FYM1	1.2	68	30	122
2.3	NPK+FYM1	1.2	116	36	145
2.4	NPK+FYM1	1.2	139	39	156
2.5	NPK+FYM1	1.2	169	42	167
3.1	NPK+FYM2	3.2	9	24	100
3.2	NPK+FYM2	3.2	52	30	121
3.3	NPK+FYM2	3.2	77	31	126
3.4	NPK+FYM2	3.2	118	37	149
3.5	NPK+FYM2	3.2	150	42	164
4.1	NPK+Straw	2	65	34	123
4.2	NPK+Straw	2	101	38	141
4.3	NPK+Straw	2	138	43	159
4.4	NPK+Straw	2	161	45	163
4.5	NPK+Straw	2	191	47	169

Source: Rogasik et al. (1997)

*Fertilizer treatments until 1993 in the crop rotation: silage maize (1963), winter rye (1964), potatoes (1965), winter rye (1966), potatoes (1967), spring wheat (1968), sugar beet (1969), spring barley (1970), silage maize (1971), winter rye (1972), potatoes (1973), winter wheat (1974), sugar beet (1975), summer barley (1976), sugar beet (1977), spring barley (1978), sugar beet (1979), spring barley (1980), sugar beet (1981), spring barley (1982), potatoes (1983), winter wheat (1984), sugar beet (1985), spring barley (1986), potatoes (1987), winter wheat (1988), sugar beet (1989), spring barley (1990), potatoes (1991), winter wheat (1992: time of soil sampling), sugar beet (1993)

3. Context of the case study

Geographical location: 15374 Müncheberg, Germany, 52.516931° N, 14.121930° E

Pedo-climatic context: According to the German Guidelines Soil Assessment (Bodenschätzung) the dominating soil types are slightly loamy sand and sand (Sl4D and S4D) with sand contents above 70%. The most common soil sub type is Haplic Luvisol. According to the IPCC, climate is cool temperate moist. The site is characterized by dry periods, particularly during early summer. Weather data for the running period of V140 are available at the homepage of the German Weather Service (DWD) (station number 03376). Data presented here are for soil samples in autumn 1992, a relatively dry year with an annual precipitation of 418 that is 103 mm less than the long-term average.

Land-use: field crops: spring barley, potatoes, winter wheat, sugar beet in rotation since 1982 until 1992. After that, flax and peas were added to the crop rotation.

4. Possibility of scaling up

It is a context-specific case study.

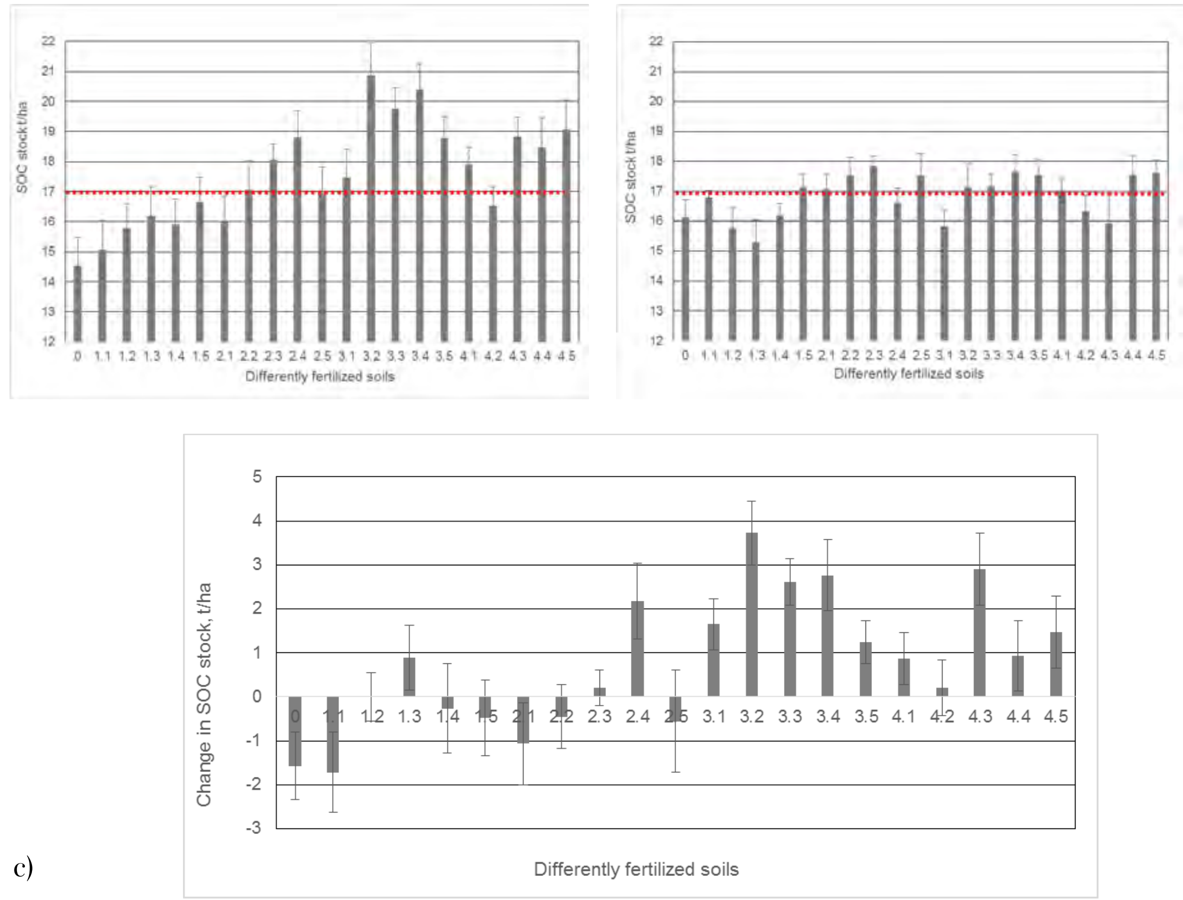
5. Impact on soil organic carbon stocks

In 1963 the mean SOC stock in the upper 0-20 cm of the soils at the field experiment was 17 t/ha. In autumn 1992, i.e. 29 years later, on average the farmyard manure (FYM) + NPK fertilized soils (treatments 3.1 to 3.5) had the highest SOC stocks (Figure 16a). The FYM fertilized soil (3.2) contained about 21 t/ha, which is about 4 t/ha more than the mean SOC stock of the 1963 samples, while the NPK fertilized soil (1.5) had a SOC stock of 16.2 which is about 0.8 t lower. The differences between the SOC stocks of FYM+NPK fertilized soils (in mean 19.6 t/ha) and that of the unfertilized soil (14.3 t/ha) were up to 3.5-times larger than the measurement error (1.5 t/ha). However, such differences were only found for the treatments 3.2, 3.3 and 3.4 (Figure 16a) and it needs to be noted there are also years in which the differences in SOC contents are less than or equal to the measurement error.

For a more precise comparison the SOC contents of specific plots need to be compared one by one, which has not been done yet. However, due to site heterogeneity with respect to texture and bulk density the SOC stocks vary to a large extent (ranging from 10.1 to 24.4 t/ha) resulting in high standard errors (0.5 up to 1.1 t/ha) for samples from plots that received the same fertilization but originated from different replicates in the experimental field.

In summary, the combination of mineral fertilizer with a high proportion of manure had the most favorable effect on the amount of SOC in the years under investigation. Pure mineral fertilization (NPK) was the least able to contribute to increasing the SOC stocks on average (Schubert, 2008) which is also described by Smukalski *et al.* (1990) for mean data of a 25-year period. The difference between SOC stocks of the 1992 samples and those of the 1976 samples can be used as an estimate for the SOC sequestration potential of the differently fertilized soils for a 16year period (Figure 16c). These SOC changes within the 16year period between 1976 and 1992 suggest the highest SOC sequestration potential (0.23 tC/ha/yr) for the 3.2 treatment (FYM + N) but a SOC loss for the control (0.11 tC/ha/yr), the 2.1 (0.067 tC/ha/yr) and the 1.4 (0.02 tC/ha/yr) treatment.

SOC stocks varied strongly from year to year: In 1970 there was a large difference in the SOC stocks of the differently fertilized soils which became smaller in 1978, but larger in the following years with the highest difference in 1992. However, in 1994 and 1996 SOC differed to a smaller extent as compared to the 1992 data. Such a constant rate in SOC sequestration or loss per year cannot be stated and we only show the change in SOC stocks for the 1992 samples as compared to those of the 1976 samples (Figure 16c).



a)

b)

c)

Figure 16. SOC stocks in t/ha on 0-20 cm depth of the differently fertilized soils

These soils were sampled in a) 1992 and b) 1976, mean over eight replicates (descriptions of treatments are shown in Table 47; red dotted line indicate the mean SOC content of the soils sampled in 1963) (Schubert, 2008; Smukalski et al., 1990) and c) the change in SOC stock (tC/ha) for a 16-year time period estimated from the differences between data of the 1992 and 1976 samples.

6. Other benefits of the practice

6.1. Improvement of soil properties

Physical properties

Bulk density in 1992 varies between 1.29 and 1.74 with a mean of 1.49 g/cm^3, which is higher than the bulk density in 1976 that varies between 1.23 and 1.51 with a mean of 1.38 g/cm^3.

Chemical properties

Samples taken in 1992 were analyzed for SOC content and for soil organic matter properties by using FTIR spectroscopy.

In addition to SOC contents the soil samples were analyzed using Fourier Transform infrared (FTIR) spectroscopy to characterize the composition of the soil organic matter with respect to the content of hydrophilic groups (C=O/COC, Ellerbrock and Gerke, 2013). The C=O/COC ratio can be used as an indicator for the hydrophilic character and the potential cation exchange capacity of the soil organic matter (Kaiser, Ellerbock and Gerke, 2008). The higher the C=O/COC ratio the more hydrophilic the soil organic matter becomes. More hydrophilic soil organic matter is able to store higher amounts of water which is related to an increased soil water-holding capacity.

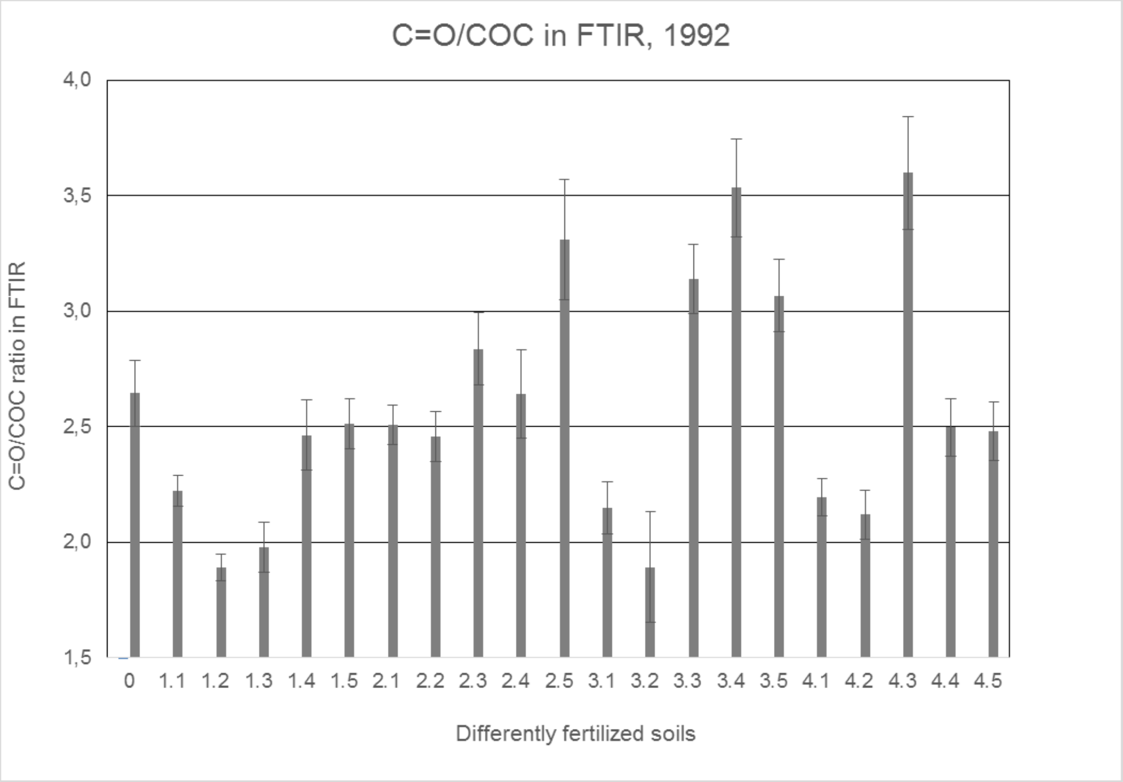


Figure 17. The C=O/COC ratios in FTIR spectra of differently fertilized soil sampled in 1992

Mean over eight replicates (descriptions of treatments are shown in Table 47). Error bars represent standard errors.

All soils fertilized with NPK only (Treatment 1) show lower C=O/COC ratios as compared to the control (Figure 17), while the FYM fertilized soils combined with higher amounts of N (Treatments 2, and 3 sub-levels 3 to 5) show higher C=O/COC ratios. For straw application (Treatment 4) such effect is only observed for sub-level 3 (Figure 17). Such change in soil organic matter composition caused by FYM application may result in an increased water-holding capacity of the soils. This may explain why the crop yield on the FYM fertilized soils are in the dry year 1992 higher as compared to that on the mineral fertilized soils (see section 6.3).

However, according to Smukalski *et al.* (1990) liming is needed to reduce a potential decrease in pH caused by organic fertilization and the heterogeneity of the field needs also to be considered since it affects at least the SOC content (see above).

Biological properties

Properties were not assessed.

6.2 Minimization of threats to soil functions

Table 48. Soil threats

Soil threats	
Nutrient imbalance and cycles	N use by plant was analyzed by Smukalski *et al.* (1990) among others. The Nt levels showed changes corresponding to the organic soil content levels. N intake higher than N deprivation was not sufficient to maintain soil N unless the reproduction of the organic soil content was assured (Smukalski *et al.*, 1990). FYM fertilization enriched the content of lactate-soluble P3 in soil while an effect on lactate-soluble K was not observable (Smukalski *et al.*, 1990).
Soil water management	Fertilization with FYM seems to increase the water-holding capacity of the soil because of its effect on soil organic matter composition (higher C=O/COC ratios with FYM fertilized soils).

6.3 Increases in production (e.g. food/fuel/feed/timber)

The plots on which only mineral fertilizer was applied vary in their yields. With a few exceptions, the yields increase with the amount of NPK, i.e. the greatest yields in general for solely mineral fertilized soils were achieved with the fertilizer treatment 1.5 (= highest level of mineral NPK fertilization). However, in 1992 - a very dry year - the combined treatments of mineral and organic fertilization (especially treatments 2.5, 3.4 and 4.5) achieved greater yields than the NPK fertilization (Schubert, 2008).

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[3] Lactate soluble cations are potentially soluble in the soil solution such that they are –in general- available for plants.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 49. Soil threats

Soil threats	
Soil erosion	Although the site is not a hilly site, after rainfall events small changes in elevation may be detectable and a digital elevation model (DEM) of the field experimental areas indicates up to 1 m differences in elevation, leading to potential effects of erosion on the SOC contents (Deumlich *et al.*, 2018).
Soil acidification	Liming is needed to reduce a potential decrease in pH caused by organic fertilization (Smukalski *et al.*, 1990).

7.2 Increases in greenhouse gas emissions

Possible GHG emissions such as N_2O from manure have not been measured in the frame of this study.

8. Recommendations before implementing the practice

According to the results of the Müncheberger long-term field experiment “V140” (Nährstoffsteigerungsversuch), it is recommended to fertilize sandy soils with a combination of FYM and mineral fertilization.

9. Potential barriers for adoption

Table 50. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Access to manure may be restricted due to a tendency to stockless arable farms and regional separation of livestock and arable production.
Institutional	No	According to the new fertilizer ordinance, in nitrate-contaminated areas from 2021 on it is not allowed to spread FYM between 1st of November and 31st of January (BMEL, 2020).

Photo

Photo 24. The 168 plots of V140 (Nährstoffsteigerungsversuch), Müncheberg, Germany

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13. Avoidance of land use change (LUC) from grassland to arable land, Germany

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1. Related practices

Conversion of grassland to cropland and cropland to grassland

2. Description of the case study

The case study is about maintaining grassland instead of converting it to cropland (land use change, LUC) and the benefits of maintaining it as grassland. The measured values cover two sites which have been converted from grassland to cropland. The gains of carbon and soil biodiversity are beneficial when avoiding the conversion of grassland to cropland. It is common that permanent grassland soils have a higher soil carbon density/stock compared to cropland soils. Therefore, the conversion of grassland to cropland soils is always associated with a loss of soil carbon.

The long-term soil monitoring sites are located in the Northern Germany (Schleswig-Holstein) and have been managed by farmers considering both production and economic benefits. The study sites are part of a high-quality soil monitoring network with standardized sampling design since 1989. The aim of the study was to demonstrate the ability of accounting changes in soil carbon in the monitoring network. The measurements were taken before and up to seven years after the conversion of the study sites, so as to consider the sites as a mid-term example.

Since the introduction of European Union (EU) regulation for direct payments from 2013 (Eur-LEX, 2013), it is forbidden to convert permanent grassland to cropland in the EU. Grassland of a minimum age of five years has been defined as permanent grassland. In this case study, the measurements after conversions were done in 2010 and 2019.

3. Context of the case study

The location is Northern Germany, and has a temperate-oceanic climate, and the two sites have a) sandy loam Stagnosol soil (54°24 N, 9°12 E) and b) clay loam Planosol soil (54°19 N, 8°38 E). Both were formerly grassland soils, which were converted to cropland in 2002 (sandy loam soil) and 2009 (clay loam soil).

4. Possibility of scaling up

It is a context-specific case study. The practice can be scaled up in the European Union as there is a prohibition of converting permanent grassland (at least 5 years long) to cropland.

5. Impact on soil organic carbon stocks

The C sequestration values should be interpreted as carbon sequestration potential if the grassland is not converted to cropland. The values in Table 51 were measured after seven (upper row) and one year(s) (lower row) after conversion from grassland to cropland, respectively. Most of the carbon loss always takes place in the first year or within a few years after conversion.

Table 51. Evolution of SOC stocks with conversion of cropland into grassland

Location	Context	Cseq potential (tC/ha)	Cseq potential (tC/ha/year)	Reference
Northern Germany	The measurements included the topsoil (0-30 cm).	19.4	2.82	Nerger, Beylich and Fohrer, (2016)
		27.2	27.2	

6. Other benefits of the practice

6.1. Improvement of soil properties

One of the main benefits of maintaining grassland land use is the higher soil biodiversity compared to the conversion/LUC to cropland. After LUC to cropland, the soil fauna was highly affected, earthworm abundance decreased by 75 percent and their biomass by 86 percent. The measurements were taken 5 years after LUC in a sandy loam soil (Nerger, Beylich and Fohrer, 2016).

Soil microbes were affected as well. The microbial biomass decreased by about 50 percent in the sandy loam soil and ˜70 percent in the clay loam soil after LUC. Similar results were observed for the microbial (basal) respiration (Nerger, Beylich and Fohrer, 2016).

In addition, maintenance of grasslands often lowers bulk density and soil compaction compared to cropland. The use of heavy machinery during ploughing and other practices resulted in soil compaction particularly below the plough layers. At the study site, the soil bulk density increased after the conversion of grassland to cropland. However, in some cases the opposite effect may occur, for example in heavy loam or clayey soils where frequent soil tillage or ploughing contributes to a lower topsoil bulk density.

6.2 Minimization of threats to soil functions

Table 52. Soil threats

Soil threats	
Soil erosion	Grassland soils with a sufficient plant coverage could lower soil erosion.
Soil contamination / pollution	Generally: It is possible that cropland is fertilized with sewage sludge or liming. These substances might contain heavy metals. Also, synthetic and organic fertilizers may contain measurable heavy metals contents. These risks would be prevented when avoiding the conversion to cropland.

Soil threats	
Soil biodiversity loss	Biodiversity in grassland soils is much higher than in cropland soils (Nerger, Beylich and Fohrer, 2016).
Soil compaction	May occur if heavy machiney is used on cropland soils.

6.3 Increases in production (e.g. food/fuel/feed/timber)

There can be an effect on food production, as grassland can be used as pasture and thus there is meat or dairy production. At the sites of this case study, there was meat and dairy production which was continued on other field and indoor after conversion to cropland.

6.4 Mitigation of and adaptation to climate change

Another GHG benefit could be the potential saving of (synthetic) fertilizer, which is often used on cropland soils. Even in cases where grassland soils are fertilized the amounts of fertilizer used are lower. Fertilizers, especially synthetic fertilizers feature a high GHG emission footprint due to fertilizer production process but also due to increased N_2O after application.

Furthermore, grassland soils are characterized by a much lower (or non-existent) soil erosion and a much lower nitrate leaching. This saves carbon in the soil and avoids the N_2O emissions.

6.5 Socio-economic benefits

The avoidance of a grassland conversion can mean a financial loss to farmers, as arable land may be more profitable, for example through the European CAP policy of energy crop premiums (which was however ended in 2010). In this case study, the grassland was converted to cropland for the purpose of growing energy crops, which were subsidized by the Government at that time. Since 2015, the Greening policy of the CAP regulates that the avoiding the conversion of environmentally valuable grasslands is coupled to 30 percent of direct payments for farmers receiving an area-based payment.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 53. Soil threats

Soil threats	
Soil erosion	Generally, grassland with a sufficient plant coverage could lower soil erosion compared to cropland soils).
Soil contamination / pollution	A possible residual contamination after fertilization with sewage sludge or liming (but also synthetic and organic fertilizers) containing heavy metals may occur.
Soil biodiversity loss	Less biodiversity loss from grassland compared to cropland soils (Nerger, Beylich and Fohrer, 2016).
Soil water management	The conversion of grassland to cropland decreased the non-plant available soil water content and increased aeration. Thus, plant available soil water may improve after conversion to cropland.

7.2 Conflict with other practice(s)

Maintaining grassland instead of converting it to cropland can cause economic conflicts with agricultural practices to adopt, as the former is often profitable more than grassland/pasture farming.

7.3 Other conflicts

Possibly an increase in commodity prices and global demand for cereals and energy crops.

8. Recommendations before implementing the practice

A cost-benefit check should be made, where the benefit side should include not just the direct economic benefits but also the benefits for the soil health, waterbodies, environment, and the agroecosystem. Finally, these could also bring economic benefits as intact agroecosystems with healthy soils, high soil organic matter content and high soil biodiversity are the basis for achieving a long-term sustainable and successful farming.

9. Potential barriers for adoption

Table 54. Potential barriers to adoption

Barrier	YES/NO	
Economic	Yes	The avoidance of a grassland conversion can mean a financial loss to farmers, as arable land may be more profitable. However, specifically in the European Union, this is no longer a barrier (or at least less important) since the Common Agricultural Policy (CAP) changed in 2015 and a significant part of direct payments is coupled to the conservation of permanent grassland.
Legal (Right to soil)	Yes	In case of rented land, it is possible that there might be compulsory conditions for managing the rented land as cropland.
Knowledge	Yes	There might be knowledge gaps in assessing the value of (permanent) grassland, considering all above-mentioned benefits. Likewise, knowledge gaps can exist in making the maintenance of grassland profitable.

Photo

Photo 25. This picture illustrates the negative practice of converting grassland to cropland in the temperate zone (Europe, Germany)

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14. The biochar challenge in viticulture: long-term experiment in Central Italy

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1. Related practices

Biochar

2. Description of the case study

Recent studies demonstrate that the Mediterranean region must urgently develop climate change adaptation plans for viticulture, especially for efficient irrigation, water use or waste-water reuse (Santillán *et al.*, 2019). Vineyard managers' interest in biochar has increased because of its potential to increase soil water-holding capacity and thus aid grape production during drought (Baronti *et al.,* 2014). Moreover, vineyard biomass from vine removal and pruned wood can be converted to biochar hence supporting a circular economy perspective.

The present work, started in 2009 in Tuscany-Italy by the CNR-IBE (National Research Council- Institute of BioEconomy) is ongoing, and aims to assess the impact of biochar on vineyard in terms of carbon sequestration, grape quality and production, soil fertility and soil contaminants in the short and long-term. The results collected during these years are exciting: in the long term it is observed that biochar application not only has potential contribute to carbon sequestration, but also has a positive effect on chemical and biological soil parameters.

3. Context of the case study

The long-term field experiment was established in a vineyard of the ″Marchesi Antinori - Tenuta La Braccesca″ (Lat. 43°10′15″N; Long. 11°57′43″E; 290 m a.s.l.), located a few kilometers from Montepulciano (Tuscany, Center of Italy). The vineyard was planted in 1995 (cv. Merlot, clone 181; rootstock 3309 Couderc), the trellis system is a curtain with spacing between the rows of 0.8 m and 2.5 m; the orientation of the rows is East - West. The vineyard is not irrigated. The morphology of the area is gently rolling with slope between 1.7

and 3.4 percent. The soils, formed on quaternary (middle and late Pleistocene) fluvio-lacustrine terraced deposits, are classified as Profondic Stagnic Luvisols (IUSS Working Group WRB, 2015). Topsoil texture is sandy loam to clay loam (USDA, 2005), with an increase in clay and silt content with depth where poor drainage can occur. The roots of the vineyards mainly explore the top 50 cm layer of soil.

Biochar was applied with two treatments, as follows: one application (22 t/ha in 2009) (B); two applications (22 t/ha in 2009 and 22 t/ha in 2010) (BB) and control untreated plots (C). The experiment, with three treatments and five replicates, was set up in 2009 and is still ongoing. Each of the 15 plots has a total area of 225 m^2 (7.5 m wide and 30 m long) including 4 rows of vineyards and 3 inter-rows.

Biochar was applied in the inter-row space of the vineyard using a spreader and it was incorporated into the soil at 30 cm depth using a chisel plow tiller. Biochar was provided by "Romagna Carbone s.n.c." (Italy) obtained from orchard pruning biomass following slow pyrolysis at 500 °C. Table 55 describes the main biochar characteristics. All chemical and physical characteristics of biochar are provided in Baronti *et al.* (2014). Water content of biochar was 25%; therefore, each biochar application of 22 t/ha corresponded to 16.5 t/ha of dry biochar.

Table 55. Biochar characteristics

	Unit	Value
C	%	77.81
N	%	0.91
C/N	-	63.53
pH	-	9.8
CEC	cmolc/kg	101

4. Possibility of scaling up

The experiment covered 1 hectare of surface in a Tuscan vineyard context, with an acidic and compact soil. Certainly, biochar can be used in all vineyard contexts, paying attention to type of soil, type of biochar and the climatic zone (Lehmann *et al.,* 2015)

5. Impact on soil organic carbon stocks

The soil carbon stock (CST, t/ha) was calculated based on soil organic carbon content (Corg) in volume (%) and soil bulk density (BD, t/m^3) for the first 30 cm of soil, which is the layer most susceptible to human disturbance:

$$\text{CST (t/ha)} = \text{Corg (\%)} \times 0.30 \times \text{BD } (t/m^3) \times 100 \qquad [1]$$

Table 56. Soil organic carbon stock changes after biochar application on a Tuscan wineyard

Location	Climate zone	Soil texture	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Year)	More information	Reference
Tuscany, Italy	Cfa (Temperate, no dry season, hot summer)	Sandy loam to clay loam	33.93 (0-30 cm)	184.47 in B soil 198.30 in BB soil	1	B: soil with a single biochar application BB: double biochar application	Maienza *et al.* (2017) Rombolà *et al.* (2015) Giagnoni *et al.* (2019)
				48.16 in B soil 56.77 in BB soil	3		
				10.98 in B soil 11.21 in BB soil	10		

In general, the conversion of biomass into biochar and its application to soil is a strategy for C sequestration in soil, which could contribute to "negative emissions". In our 10-year experiment, soil organic carbon increases in the early years (1-3 years after applying biochar) and the initial soil carbon content increase remains even after 10 years.

Both the double biochar amendment and single biochar application caused a consistent increase in SOC with respect to control soil in first year (198.30 tC/ha/yr and 184.47 tC/ha/yr (BB and B, respectively) and vs. control soil, 33.93 tC/ha (Table 56). The soil carbon content decreased with time throughout the sampling period but remained significantly higher (4.8-3.5%) than control (0.7-0.9%) (Rombolà *et al.,* 2015). Whereas the inorganic carbon content was negligible in these acidic soils, the total carbon content closely corresponds to that of SOC. The addition of biochar significantly increased the total SOC pool by more than six times in the early years. Three years after applying biochar (2009-2013) in the vineyard, the SOC in modified soil was still

3.8 times higher than that of the control soil. After 7 years (2009-2017) of biochar application, although the values are lower, there are still differences between the control and biochar soil (Giagnoni *et al.,* 2019). Rombolà *et al.,* 2015 showed that the majority of SOC in the control soil occurred in a semi-labile form, probably derived from a combination of lignocellulosic debris, humic acids, and microbial biomass including thermally labile charcoal. Amending the soil with biochar created the opposite situation, with the majority of the SOC pool in the form of recalcitrant carbon.

6. Other benefits of the practice

6.1. Improvement of soil properties

In this case study, the long-term impact of biochar on the physical, chemical and biological properties of the soil and on the ecophysiological parameters of *Vitis vinifera* was evaluated. After 10 years, ecophysiological measurements indicated a substantial increase in soil available water content and a significant improvement of plant water status in biochar-amended plots (Baronti *et al.,* in preparation). The modification of plant water availability induced by biochar application increased the resilience of vineyards to water shortages (droughts), as demonstrated by the lower leaf water potential, higher stomatal conductance and higher photosynthetic activity measured in biochar-amended plots in the short term (2 years after biochar application) (Baronti *et al.,* 2014) and in the long term (10 years after biochar application) (Baronti *et al.,* in preparation), generating significant impacts on quantity and quality of production after 10 years. Soil biological communities were affected by biochar additions as reflected by increase in abundance of species with soil moisture content and enhanced biodiversity (Shannon index) after 10 years (Maienza *et al.,* in preparation)

6.2 Minimization of threats to soil functions

Table 57. Soil threats

Soil threats	
Nutrient imbalance and cycles	Biochar amendment affected enzyme activities involved in long-term C, N, P and S mineralization. The biochar application after 6-7 years increased the oxidative enzyme activities and decreased carbohydrate hydrolyzing activities. The biochar-treated soils also showed enhanced soil N availability, particularly as nitrate-N and substantial total P concentration increases (Giagnoni *et al.,* 2019).
Soil contamination / pollution	No soil eco-toxicity is reported after long-term amendment using Vibrio fischeri bacteria test data (luminescent bacteria test, ISO 11348-2007) (Maienza *et al.,* 2017). No contamination in terms of total polycyclic aromatic hydrocarbons (PAHs) concentration in soil was observed for a single biochar (B) and double treatment (BB) after 1-3 years and 10 years (Rombolà *et al.,* 2015 and Rombolà *et al.,* 2019; Giagnoni *et al.,* 2019). The concentration of 16 polycyclic aromatic hydrocarbons (PAHs), issued by the U.S. Environmental Protection Agency (EPA) in the biochar was 3.8 μg/g; naphthalene was the most

Soil threats	
	abundant species (2.1 µg/g) followed by phenanthrene (0.67 µg/g). The level of PAHs fulfilled the current quality standards issued by Italian legislation (6 µg/g), European Biochar Certificate (4 µg/g for premium quality) and the International Biochar Initiative (6-300 µg/g). The bioavailable heavy metals concentration did not increase in soil after 7 years of application (Maienza *et al.,* 2017).
Soil acidification	Biochar had significant impacts on the soil pH, changing from sub acid to neutral values after 1 year (Baronti *et al.*, 2014) and 7 years (Maienza *et al.*, 2017; Giagnoni *et al.*, 2019; Rombolà *et al.*, 2019).
Soil biodiversity loss	Biochar amendment increased the total soil microbial biomass, but did not change the soil community structure (Maienza *et al.*, 2017). After 10 years, a significant increase in total abundance of micro-arthropods (especially Collembola) was observed in the soil amended with biochar (Maienza *et al.*, in preparation).
Soil compaction	The Biochar application significantly decreased soil bulk density in the short and long-term (Baronti *et al.*, 2014; Maienza *et al.*, 2017).
Soil water management	Biochar application increased available water content (AWC) and ameliorated plant water status by substantially increasing leaf water potential during the driest period of the summer when soil water is in short supply. This effect was very likely amplified under the shallow and low AWC soil conditions of our field site (Baronti *et al.*, 2014). Moreover, the water drop penetration test performed on the soil–biochar mixture compared to control soil did not highlight potential concerns associated with the increase of hydrophobicity (Baronti *et al.*, 2014).

6.3 Increases in production (e.g. food/fuel/feed/timber)

The application of biochar substantially increased the vineyard production in all harvest years (Genesio *et al.,* 2015; Genesio *et al.,* in preparation). We observed an increase of up to 66% in the grape production of the plots treated with biochar. In fact, the application of biochar increased the soil water content, and the water available to the plants, and this probably resulted in the substantial increase in productivity (yield, average cluster weight and berry size) in all crops. This effect was greater in years with lower rainfall, convincingly supporting the idea of a positive regulating effect of biochar in the event of water scarcity. Unexpectedly, no significant effects were observed on the key parameters of grape quality, suggesting that the increased availability of plant water due to biochar may have a complex mechanism of action on plant physiology and possibly involving an effect on tissue formation. In particular, the greater fertility of grapes, expressed by the number of seeds per grape, observed in our experiment, must be further investigated to consider the existence of mechanisms other than the availability of water and nutrients with particular reference to the impact of soil microbial activity (Gomez *et al.,* 2014) and plant hormone response pathways (Spokas, Baker and Reicosky, 2010).

6.4 Mitigation of and adaptation to climate change

The potential of biochar to sequester atmospheric carbon after its application has been highlighted by the IPCC (2019). Producing biochar and bioenergy via pyrolysis is a carbon-negative process. Biochar can increase SOC sequestration due to the inherent stability of some biochar components, but it can also interact with the decomposition of specific SOC fractions. For climate change mitigation, useful SOC sequestration in agricultural soils occurs when application of biochar results in a net increase in the SOC pool relative to the atmospheric CO_2 pool in a specified area over long periods of time (millennia). This topic will be addressed in the coming years.

6.5 Socio-economic benefits

The uncertainty surrounding investments in biochar production and the carbon offsets market needs to be further explored through a robust economic and full life cycle analysis. Unfortunately, socio-economic benefits were not analyzed during this study.

6.6 Other benefits of the practice

The addition of biochar to soil caused a substantial and significant change in soil physical characteristics. This was undoubtedly associated to the peculiar properties of biochar and in particular to its high specific surface area (SSA) and low bulk density. The total porosity of the biochar used was 2722 mm^3/g; storage pores were 75% of the overall porosity, residual pores 15% and transmission pores 10%. The particle size above 10 mm accounts for 16.5% of the total mass, 23.5% is between 10 mm and 4 mm, 45% is between 4 mm and 2 mm and 15% is smaller than 2 mm. The analysis of pore size distribution suggests that these changes were related to pore function as increasing values of pore diameter corresponded to decreasing values of water tension (i.e. 1 mm = pF 3.5, 3 mm = pF 3; 10 mm = pF 2.5 and so on). Transmission pores, in particular, make air and water movement easier and their prevalence is important both in soil–water–plant relationships and for maintaining good soil structure conditions. Conversely, storage pores and residual pores are responsible for the storage of plant water and the storage of micro-organisms and mineral nutrients, respectively (Sohi *et al.*, 2010). These physical properties contribute to explain how the addition of biochar increased soil water content in this experiment, thus confirming and expanding the findings of other authors, who also found enhanced water retention in sandy soils amended with biochar (Brockhoff *et al.*, 2010).

6.7 Upscaling

Under a closed farm production chain, a biochar strategy based on high distribution rates appears to be feasible only from a multi-year perspective. For instance, if we assume that in Central Italy 1 ha of vineyard produces on average 1.5 ton of dry residues (pruning) per year, and the thermo-chemical conversion of this residue yields 0.5 t/ha of biochar, a biochar application rate of 20 t/ha could be obtained from 40 hectares under a programme which rotates biochar application for 40 years. This rotation time, of course, can be reduced if other farm residues (e.g. vinasse) are channeled into biochar production, and if biochar stimulates the above ground biomass productivity, as in other crops (Vaccari *et al.*, 2011).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 58. Soil threats

Soil threat	
Soil contamination / pollution	The results from 10 years showed that the application of a premium grade biochar in soil system at double dose (44 t/ha) (BB) increased significantly the levels of PAHs in the short term (after 1-3 years biochar application) but not in for longer periods (5-7 years). Nevertheless, the concentration of total PAHs remained below the maximum acceptable concentration established in several European countries (Rombolà *et al.*, 2019).

7.2 Increases in greenhouse gas emissions

GHGs were not analyzed during this study.

8. Potential barriers for adoption

Table 59. Potential barriers to adoption

Barrier	YES/NO	
Cultural	No	The use of biochar added to soil in Italy is still in an experimental phase. There are numerous open field experiments, also some long-term experiments carried out by the National Research Council (CNR) and University, but a widespread use of biochar as an agricultural practice still does not exist.
Economic	Yes	In Italy, the biochar technology is relatively new, costs and impacts associated with it are just beginning to be explored
Institutional	Yes	In 2009 was established the Italian Biochar Association (ICHAR) to create synergy and collaboration between the research institutions and the private sector in promoting solutions, technologies, advanced studies and demonstration activities related to the use of biochar as a possible strategy to mitigate GHG emissions and simultaneously increase crop productivity. Since 2009 ICHAR partners include: Research institutions (public and private); Biochar producers; Public administrations; Farmers and companies in the agri-food sector; organic farming organizations.
Legal (Right to soil)	Yes	On 12 August 2015, the edition No. 186 of the Italian law gazette "*Gazzetta Ufficiale Della Republica Italiana*" published a modification of the Annexes 2 and 7 of the fertilizer decree number 75 of 29 April 2010. With these modifications, made following a request presented by the Italian Biochar Association (ICHAR), the Italian Ministry of Agriculture, Food and Forestry included biochar in the list of soil amendments which are permitted to be used in the Italian agricultural sector and defined technical specifications for this product. The revised version of Annex 2 includes thresholds for heavy metals and defines three biochar quality classes based on C and ash content. Thresholds for organic pollutants have been set by the decree of 28.06.2016 in GU Serie Generale n.188 (see *Ministero delle politiche Agricole alimentary e forestali,* 2016). A further modification of the Annex 13 for the inclusion of biochar in the list of amendments allowed in organic agriculture has been requested by ICHAR and is actually, accepted of the Ministry of Agriculture, Food and Forestry.
Knowledge	Yes	Biochar is not widely known among vineyard farmers
Natural resource	Yes	In Italy the biochar must be produced exclusively from traceable biomass of vegetal origin from the agro-forestry sector. No wastes and animal manures.

Photos

Photo 26. The biochar distribution at the beginning of the long-term experiment in 2009, La Braccesca Estate, Montepulciano (AR), Italy

Photo 27. The biochar distribution at the beginning of the long-term experiment in 2009. La Braccesca Estate, Montepulciano (AR)-Italy

Photo 28. Vineyard experiment in 2020

Sx after 10 years of biochar application, dx control without biochar. La Braccesca Estate, Montepulciano (AR)- Italy

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15. Conservation agriculture practices in North Italy

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1. Related practices

Conservation agriculture, adequate irrigation practices

2. Description of the case study

The comparison of Conservation agriculture systems with conventional "arable" agriculture in North Italy was the aim of the Life HelpSoil project, which started in 2013 and ended in 2017 (http://www.lifehelpsoil.eu). To this purpose, a large set of agronomic and environmental indicators was monitored for three consecutive years in 20 experimental sites located on real farms. Each site was arranged with two test plots, cultivated under conservation and conventional practices, respectively. Conservation practices included the implementation of three treatments: 1) minimal soil disturbance, by the adoption of no-tillage and, in some farms, minimum tillage techniques; 2) permanent soil cover, by using cover crops and returning crop residues on the soil surface; and 3) improved crop rotation, by expanding the number and the diversity of species cultivated. These were compared to conventional practices consisting of a "business as usual" approach which was preparation of soil beds for seeding with a moldboard plough, to a depth of 30-40 cm, followed by soil refinement operations. Measured soil indicators included soil organic carbon (SOC) sequestration potential, soil biodiversity (earthworms abundance, the QBSar (Soil Biological Quality) index that is based on the presence/abundance of microarthropods (Menta *et al.*, 2018), soil biological activity (Soil Biological Fertility (IBF) Index), soil erosion occurrence, and soil aggregate stability. In addition to soil health, fossil fuel consumption for tillage and soil management operations and water demand for irrigation and crops yield were recorded. The overall effect of the conservation agriculture practices was positive and showed a considerable beneficial impact of soil conservation management practices on SOC storage; soil fertility, soil biodiversity and climate agro-ecosystem services supply are also improved, while enhancing the quality of rural environment and maintaining the profitability of cropping systems (Brenna and Tabaglio, 2017).

3. Context of the case study

The study was carried out in North Italy, on an area covering the whole Po Plain and the bordering hilly landscapes of the Alpine and Apennine margin, where agriculture is very intensive. Experimental sites were characterized by different soil types, classified as Luvisols, Vertisols, Cambisols and Fluvisols (IUSS-WRB, 2007). Soils have a clay content in the topsoil ranging from 7 to 49 percent, and a pH from 5.6 to >8. Across the Po Plain, cropland soils show low levels of soil organic carbon content (SOC), ranging from 34 to 60 tC/ha in the first 30 cm of depth, due to intensive exploitation in the past, and therefore have a large potential to re-gain carbon, if they are managed by adopting suitable practices. The main cropping systems across this region are cultivation of winter cereals (wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*)) alfalfa, and summer crops (maize (*Zea mays*), soybean (*Glycine max*) and sorghum (*Sorghum bicolor*)). Rice was cultivated in one of the experimental farms. Winter cover crops, formed by cereals (Italian ryegrass, Triticale) or a mix of different species (Vetch (*Vicia sativa*), Rye (*Secale cereale*), Italian Ryegrass, Radish (*Raphanus sativus*)) were sowed in the study sites managed under conservation practices. The farms where study sites were located were irrigated, except for those located in the hilly area. Some of them are dairy farms and soils were fertilized with manure applications. The mean annual rainfall in the area ranged from about ~650 mm/yr to more than 1000 mm/yr.

4. Possibility of scaling up

Cropland covers about 4.5 million hectares or 38 percent of the land area of North Italy. Of this area, only 4.5 percent of croplands are currently managed through reduced tillage practices. Nevertheless, conservation practices draw an increasing interest because of the contribution to the mitigation and adaptation to climate change. The results of the Life HelpSoil project evaluated the incentives provided for farmers in Italy by the Rural Development Plans to shift from conventional to conservation management practices. These incentives are part of a broader strategy aimed at supporting the development of agricultural practices that not only support provisioning services (i.e. food) but also other supporting and regulating services such as climate change mitigation and adaptation, soil erosion control, improved water quality and enhancement of biodiversity. The results achieved in the Life HelpSoil project are similar to those observed in many other studies carried out in Italy and around the world, confirming that soil carbon sequestration through the adoption of conservation management practices can actually be considered as a viable way to increase the sustainability of cropping systems while supplying of public goods for society (Brenna, Piazzi and Rocca, 2016; Brenna and Tabaglio, 2017). Scaling up conservation practices, however, requires investment in the development of technical assistance services. This technical assistance would allow farmers to improve their crop management strategies and cultivation methods and overcome the concerns about techniques that are not routinely adopted. The unavailability of suitable equipment (e.g. sod seeders) or the incorrect management of cover crops may also hamper the adoption of such practices.

5. Impact on soil organic carbon stocks

The results of the study indicated that on average, plots managed under conservation practices had a 7.3 percent higher SOC stock than conventionally managed plots respectively (63.4 tC/ha and 59.1 tC/ha) (Perego *et al.*, 2019). However, in some sites characterized by plots where conservation practices have been already applied for at least 8-10 years before the beginning of the project a SOC stock exceeding 70 tC/ha was detected. The minimum SOC stock (43.5 tC/ha) was found on a conventionally managed plot. Potential of additional C storage has been estimated ranging up to 0.6-0.8 tC/ha/yr. Moreover, a modelling approach was also used to assess the carbon balance of conservation and conventional practices. Model simulations (ARMOSA model) suggested that conservation practices, if fully applied, can increase the SOC stock at a rate up to 0.4-0.5 tC/ha/yr (Perego *et al.*, 2019). Results showed however a strong variability depending on soil types and cropping systems that may influence the variation of SOC stocks (Valkama *et al.*, 2020). The cultivation of cereals, oil, forage and other herbaceous crops can in particular benefit from conservation practices; the introduction of cover crops into crop rotations allows higher additional SOC storage when conservation practices are applied and limits carbon losses from ploughed soils under the pedoclimatic conditions of North Italy (Table 60). Soils with a relatively high content of clay were more responsive to SOC accumulation compared to silty textured soils. In any case, the data provided with the Life HelpSoil project confirmed that cropland can be managed using conservation practices to sequester carbon and increase SOC stocks.

Table 60. Evolution of soil organic carbon stocks with conservation agriculture practices in the Po Plain

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Po Plain, North Italy	Warm Temperate Moist	Cambisols Luvisols, Vertisols Fluvisols	59,1	Up to 0.6 - 0.8	5-10	0-30	Baseline measured on conventional managed soils (average value)	www.lifehelpsoil.eu
				0.4 - 0.5	20		Based on model simulation	

6. Other benefits of the practice

6.1. Improvement of soil properties

Conservation management practices have proven to improve many soil properties and qualities. All sites managed under those practices in the Life HelpSoil case study showed higher soil aggregate stability, increased water infiltration and water holding capacity, lower soil penetration resistance, enhanced soil biodiversity and biological activity (Fiorini *et al.*, 2020).

6.2 Minimization of threats to soil functions

Table 61. Soil threats

Soil threats	
Soil erosion	Sheet and rill erosion strongly reduced, due to permanent soil cover (cover crops and/or crop residues left on the surface of land) and higher aggregate stability, that protect soil from the forces of raindrops and prevent overland flow.
Nutrient imbalance and cycles	Overall, nutrient availability for plants improved and losses were reduced.
Soil contamination / pollution	Soil cover (cover crops and crop residues) enhance filtering and buffering land capacity.
Soil biodiversity loss	Earthworms from 2 to 3 times more numerous under Conservation agriculture (321 vs 123 individuals per m^2) and microarthropods 30 percent more abundant (QBSar index 83 vs. 63).
Soil compaction	Water ponding and soil surface crusting usually reduced water stability index (WSI) of soil aggregates 47-49 percent higher in all soil types.
Soil water management	Improved water efficiency, by reducing evaporative losses and percolation and increasing soil water retention and the storage, over time, of rain and irrigation water.

6.3 Increases in production (e.g. food/fuel/feed/timber)

The Po Plain is a highly productive agricultural area and benefits of conservation soil management practices have been found mainly to result in more stability of crops yields year by year. However, a slight reduction of yields could be expected, especially in the first years after conservation practices started to be implemented. Weeds control is often the most critical issue. Moreover, maintaining the same yield level for rice cultivation has been shown more challenging, even if the improvement and the adaptation of practices over the time should allow to gradually close the existing gap (Brenna and Tabaglio, 2017).

6.4 Mitigation of and adaptation to climate change

Fuel consumption was strongly influenced by the considerable differences between farms, accounting on average for similar values. However, the study showed how fossil fuel consumption for mechanical operations can actually be lowered (till to -50-60 percent) and indirect CO_2 emission also decreased, due to reduced mechanization, when conservation practices are carefully applied. In that case, emission saving of up to 500-750 kg CO_2eq/ha/yr under no-tillage and up to 150-200 kg CO_2eq/ha/yr under minimum tillage practices has been estimated in the experimental sites, which is due to lower diesel use. The full carbon footprint analysis

(LCA methodology) showed high variability according to the large difference in cropping systems and mechanization of farms. Overall, the adoption of conservation practices generally allowed for a lower carbon footprint (from some hundred to thousand kg CO_2eq/ha/yr depending on the farm) that was far down if also SOC sequestration was accounted (often stating in this case a negative emission condition). Finally, even though not directly assessed in the Life HelpSoil study, based on literature available there are reasonable grounds for considering that CH_4 and N_2O emissions did not differ significantly between conservation and conventional management practice. Instead, the contribution to climate change adaptation and mitigation is provided in terms of improvement in water and air quality, regulation of water outflows, flooding risk reduction, increased slope stability and decline in soil erosion risk, and enrichment of landscapes and biodiversity.

6.5 Socio-economic benefits

Shifting from conventional to conservation regimes should be viewed as an investment that is capable of delivering benefits especially over time scales of 5-7 years, according to our experience and depending on farms and soil type. In fact, once the "soil-cropping system" has reached the new equilibrium, it can offer greater profit margins, reducing production costs and saving time that can be dedicated to diversifying farming activities or developing innovation (Brenna and Tabaglio, 2017). The experience gained in the Life HelpSoil project suggests that, even if results often are not immediate, in the long term also a positive economic feedback occurs; in particular, soil compaction, weed control and cover crop management have been shown to be the most relevant aspects involved in securing economic benefits. Moreover, study results contributed to raise awareness that through a more careful and less impacting use of soil resources it is possible to achieve a more effective protection of farmers' incomes, mainly through the reduction of production costs and according to the CAP (Common Agricultural Policy) goals.

7. Potential drawbacks to the practice

6.1 Tradeoffs with other threats to soil functions

Table 62. Soil threats

Soil threats	
Nutrient imbalance and cycles	Difficulties in manure management may arise in livestock farms.
Soil contamination / pollution	Weeds control sometimes may be critical. Proper management of crop residues and cover crops is essential.
Soil compaction	Soil structure is more stable, but soil compaction must be avoided, making sure field works are carried out when soil conditions are optimal and using suitable machinery.

7.3 Decreases in production (food/fuel/feed/timber/fibre)

After the switch to conservation practices, a transition period can occur, when the crops yields declined before rebounding to yields previously observed. HelpSoil plots, where such practices were implemented long before the study, showed similar production to ploughed fields. Summer crop yields (maize, soybean) was 15 percent lower on average in the plots most recently converted. However, in most soils and crops the transition period where lower crop yields were observed was approximately 5 years.

8. Recommendations before implementing the practice

Outcomes are often strongly influenced by a relatively poor application of soil conservation principles. Thus, the investment in training for farmers and agricultural advisors and in dissemination and demonstration activities play a key role. Allowing real opportunities for farmers to share experiences, showing "good examples" through the implementation of a network of farms where best practices are applied and fostering opportunities for training courses, knowledge dissemination and exchange of information are examples of initiatives that should be promoted. Moreover, adaptation of practices to pedoclimatic conditions and cropping systems is needed as well as the awareness that the application of conservation practices improves soil functionality (soil vitality and fertility) and agro-ecosystem services (starting with C sequestration and storage) if change is not limited to the reduction of tillage operations, but also permanent soil cover and diversification of crop rotations are implemented (Brenna and Tabaglio, 2017).

9. Potential barriers for adoption

Table 63. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	All soils suitable; more frequent difficulties in silty soils.
Cultural	Yes	Education and training essential.
Social	Yes	Lack of support services and technical assistance.
Economic	Yes	Fear for yields reduction during the transition period.
Institutional	No/Yes	Subsidies to support dissemination of practices.
Knowledge	Yes	Lack of experience and skills.
Natural resource	No	All farms potentially interested, with adaptation.

Photos

Photo 29. Winter cover crop

Photo 30. Life HelpSoil study site

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16. Mediterranean olive orchard subjected to sustainable management in Matera, Basilicata, Italy

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1. Related practices

Cover cropping, organic mulch, no-till, fertigation, mineral fertilization, adequate irrigation practices

2. Description of the case study

A case study was set up in 2000 within a typical Mediterranean context to compare the effects of long-term olive orchard management - based on sustainable practices - with the agronomically ordinary management, which is widespread in the study area. Specifically, sustainable techniques have been adopted for 20 years in a mature olive orchard (1-ha wide, 156 plants/ha; plants > 70-year-old) to conserve and improve soil organic matter content, taking care to maintain olive tree productivity. The sustainable grove (S_{mng}) was drip-irrigated (on average, 2850 m^3/ha/yr) from March to October with urban wastewater treated by a pilot unit according to simplified schemes, aimed to recover organic matter and nitrogen as fertilizing substances (Palese *et al.*, 2009). A light pruning was carried out every year during winter in order to reach vegetative-reproductive balance of the trees. The soil was permanently covered by spontaneously self-seeding weeds that were mowed at least twice a year. Weeds and pruning residues were shredded and left along the row as mulch. Fertigation was applied following the nutrient balance approach, which took into account nutrient input (by wastewater), output (by yield), and recycling/immobilization in the olive grove system (by pruned material, senescent leaves, cover crops). An integrative amount of about 40 kg/ha/yr of $N\text{-}NO_3^-$ was distributed in the early spring to entirely satisfy plant nutrient needs. An adjacent orchard (1 ha) with the same characteristics was kept as 'control' (C_{mng}). It was rainfed and managed by tillage (harrowing up to 10 cm soil depth) performed 2-3 times per year in order to control weeds. Intensive pruning was carried out every two years. Pruning residues were removed from the olive orchard. Mineral fertilization was carried out empirically once per year in early spring by using granular product. The statistical analysis of the data here presented was performed using Sigmastat 3.1 software (SPSS

Inc., Quarry Bay, Hong Kong). The means of all the measured parameters were treated by one-way analysis of variance (ANOVA) with the orchard management type (S_{mng} and C_{mng}) as a factor. Means were separated according to Fisher's LSD test at $p \leq 0.05$. Five analytical replicates for each treatment from five independent composite soil samples ($n = 5$) were considered.

3. Context of the case study

Olive is a widespread crop within Mediterranean area and Italy is one of the biggest producer of olives and oil in the world (IOC, 2020). Italian olive growing is characterized by wide pedoclimatic conditions and topography combinations, many varieties and olive orchard management typologies, all making it a multifunctional rural activity with the most disparate objectives: economic/productive, social, landscaping, environmental, recreational, of territory protection and gastronomic tourism.

In detail, the case study was located in Southern Italy, Basilicata region, in a village named Ferrandina within Matera Province (40°29' N; 16°28' E). The autochthonous cultivar "Maiatica di Ferrandina", widespread in that geographical location, is a dual-purpose cultivar producing good oil and tasty table olives. These last are harvested at black maturity stage and then processed according to a typical local method in order to obtain oven dried drupes, an excellent specialty of Ferrandina (Brighigna, 1998).

The area is characterized by a warm temperate dry climate, with an annual rainfall of 558 mm (mean 1995-2017) and a mean annual temperature of 16.0 °C. The soil is a sandy loam, Haplic Calcisol with sediment as parental material (Lal, 2017). The coverage of the case-study can be defined as local.

4. Possibility of scaling up

Given the importance of the olive growing and the area covered by this crop, the study can be adapted for scaling up for the whole Mediterranean area (9,800,000 ha covered by olive, with 1,200,000,000 plants).

5. Impact on soil organic carbon stocks

Table 64. SOC stocks changes after 20 years of implementation of SSM on the olive grove plantation

Soil depth (cm)	Baseline SOC stock (t SOC/ha) [a]	Additional SOC storage potential (t SOC/ha/yr)	SOC stock after 20 years of sustainable management (t SOC/ha)	References [b]
0-5	7.20 ± 1.49 b	0.61 ± 0.07	19.39 ± 0.13 a	Sofo, Mininni and Ricciuti (2020); Sofo *et al.* (2019a, 2019b); Palese *et al.* (2014)
5-10	8.26 ± 1.04 a	0.02 ± 0.04	8.58 ± 0.21 a	
10-20	4.76 ± 0.27 b	0.14 ± 0.01	7.56 ± 0.17 a	
20-30	5.27 ± 0.64 b	0.09 ± 0.03	7.08 ± 0.08 a	
30-50	3.19 ± 1.15 b	0.08 ± 0.04	4.80 ± 0.26 a	
60-80	2.94 ± 1.37 a	0.05 ± 0.06	3.95 ± 0.26 a	
80-100	1.93 ± 0.48 b	0.05 ± 0.01	2.89 ± 0.33 a	

[a] The baseline SOC stock corresponds to Cmng after 20 years, that remains statistically unchanged during the whole experimental period

[b] Each value represents the mean (± standard deviation) from five independent composite soil samples (n = 5)

Means were separated according to Fisher's LSD test at $p \leq 0.05$

The values of SOC stock followed by different letters are statistically different ($p \leq 0.05$) between the two treatments (Smng and Cmng)

6. Other benefits of the practice

6.1. Improvement of soil properties

Physical properties:

S_{mng} system showed higher values of soil macroporosity (9.4 vs 5.6 percent v/v in the 0-30 cm soil layer), lower soil bulk density (1.25 vs 1.38 g/cm^3), and a better soil structure, characterized by macropores of smaller size (50-500 mm), interconnected and homogeneously distributed along the profile, which positively affected soil water movement (160 vs 13 mm/day water vertical infiltration). This made S_{mng} system more efficient to intercept and store water, compared to the C_{mng} soil (4.250 vs 2.935 m^3/ha water holding capacity) (Celano *et al.*, 2011; Palese *et al.*, 2014). Also, water stable aggregates (WSA) values were higher in the S_{mng} system conferring to the soil a greater structure stability (Lombardo *et al.*, 2019).

The pedological soil profiles of the 0-90 cm layer were different in the two systems because of the higher presence of grass roots and soil macrofauna in the S_{mng} system, that caused a higher soil macroporosity and a reduction in bulk density (Sofo *et al.*, 2019b).

Chemical properties:

The soil of the S_{mng} system had significantly lower pH (7.23 vs 7.91 in the 0-30 cm soil layer) , higher soil organic carbon (SOC) (13.18 vs 10.59 g/kg soil in the 0-30 cm soil layer) and soil total N (1.56 vs 1.13 in the 0-30 cm soil layer), lower C/N ratio (7.69 vs 9.33 in the 0-30 cm soil layer), higher cation-exchange capacity (CEC), and higher content in macronutrients (particularly N, P, K , but also Ca and Mg) and micronutrients (particularly Fe, Zn and Cu), compared to the C_{mng} soil (Sofo *et al.*, 2019b).

Biological properties:

The soil of the S_{mng} system had higher diversity (genetic, functional and metabolic), abundance and activity of bacteria, fungi and soil fauna (in the S_{mng} system: 35.6 bacterial CFU × 10^6 g^{-1} soil and 21.4 fungal CFU × 10^4/g soil in the 0-30 cm soil layer, and 4.011 g of earthworms and 0.552 g of other macrofauna in in a 25 × 25 × 25-cm deep soil block; in the C_{mng} system: 10.0 bacterial CFU × 10^6 g^{-1} soil and 2.9 fungal CFU × 10^4/g soil in the 0-30 cm soil layer, and 1.397 g of earthworms and 0.252 g of other macrofauna in a 25 × 25 × 25-cm deep soil block) (Sofo *et al.*, 2014; Sofo, Mininni and Ricciuti, 2020). Soil microorganisms and macrofauna responded positively to a sustainable orchard management characterized by periodic applications of locally derived organic matter (Sofo *et al.*, 2010, 2014).

6.2 Minimization of threats to soil functions

Table 65. Soil threats

Soil threats	
Soil erosion	In comparative trials performed by means of a rainfall simulator on small plots, the S_{mgn} system reduced surface runoff to approximately one-third and soil losses to zero compared with the C_{mgn} system (Palese *et al.*, 2015). The amount of Water Stable Aggregation was significantly higher in S_{mgn} system, thanks to the greater stability of the soil structure conferred by cover crops and no-tillage (Lombardo *et al.*, 2019). This decreases soil erosion risk caused by the beating action of the rain and by surface runoff and avoids the break of soil aggregates into smaller particles and the formation of the surface crust.
Nutrient imbalance and cycles	In the S_{mgn} system: the average values of organic N, P and K distributed by means of the treated wastewater were 54, 3 and 50 kg/ha/yr, respectively (Sofo *et al.*, 2019a); higher N fixation and enhanced N-cycle were found (Pascazio *et al.*, 2018; Sofo *et al.*, 2010, 2019b)

Soil threats	
	soil reserves of the main macronutrients (N, P and K) generally increased, with both low or none input of external chemical fertilizers (Sofo *et al.*, 2019b).
Soil contamination / pollution	The irrigation with treated urban wastewater in the S_{mgn} system did not cause contamination with potential human pathogenic bacteria or other contaminants/pollutants (Palese *et al.*, 2009; Sofo *et al.*, 2019a).
Soil acidification	A slight acidification (about 0.5 points of pH in the first 90 cm of soil), mainly due to the higher SOC and mineral N forms, was observed in the S_{mgn} system (Sofo *et al.*, 2019b).
Soil biodiversity	The S_{mng} system had higher abundance and activity of soil fauna (particularly earthworms), paralleled by enhanced litter decomposition and soil bioturbation (Sofo, Mininni and Ricciuti, 2020).
Soil compaction	Soil compaction, evaluated in terms of soil macroporosity, was significantly lower in the S_{mng} system (Celano *et al.*, 2011; Palese *et al.*, 2014). In the C_{mng} system, the occurrence of soil crusting and of compacted layers along the profile hindered infiltration and percolation of rainfall water influencing the soil water content (Celano *et al.*, 2011; Palese *et al.*, 2014).
Soil water management	The S_{mng} system was able to better store water from rainfall, received during the autumn-winter period, especially in the deepest soil layer. The increase in SOC and the higher macroporosity in the S_{mng} system caused a higher soil water holding capacity, compared to the C_{mng} system (Celano *et al.*, 2011; Palese *et al.*, 2014).

6.3 On production

In the S_{mng} system, higher olive yield occurred, compared to the C_{mng} system (8.4 vs 6.3 t/ha/yr, mean 2001-2016), due to higher soil water availability and, partially, to the reduction of the "off" years (years without fruits) and the larger fruit size of the S_{mng} plants.

6.4 Mitigation of and adaptation to climate change

As explained in the paragraph 5, S_{mng} soil was a significant sink for C, especially because of the supplies of the organic resources internal to the system (cover crops, pruning material). The S_{mng} system was also able to fix in its above-ground (yield, pruning material, leaf turnover, spontaneous vegetation) and below-ground components (root systems of olive trees and spontaneous vegetation), and a higher total amount of CO_2 than C_{mng} (more than the double). Spontaneous vegetation (above and below-ground parts) was the most important pool sequestering about 35 percent of the total fixed CO_2. Pruning material had a substantial importance in CO_2 fixation (Palese *et al.*, 2013).

The soil of the S_{mng} system showed an increased abundance of N-fixing bacteria and less denitrifying bacteria (Sofo *et al.*, 2010, 2019b), so acting as sinks also for N and releasing less N oxides (NO_x) (these latter are strong GHG). Higher N as result of its biological fixation often determines more chance to produce NO_x under higher soil water content but, in our case, the localized drip irrigation applied in the S_{mng} system minimized water excess and accumulation, so reducing denitrification and the consequent NO_x release (Sofo *et al.*, 2010).

6.5 Socio-economic benefits

The S_{mng} system was a much more effective management model in terms of productivity and profitability. The economic analysis showed that the gross profit of the S_{mng} was considerably higher (6276 €/ha) than the C_{mng} (1517 €/ha). This was due to the higher yield and its superior quality, which means that it can negotiate better market price than the C_{mng} system (Pergola *et al.*, 2013).

7. Potential drawbacks to the practice

7.1 Tradeoffs of the sustainable management system with other soil threats

Table 66. Soil threats

Soil threats	(See references in Section 6.2)
Soil erosion	No tradeoffs
Nutrient imbalance and cycles	It is important to mow weeds and grasses during spring, before the starting of nutrients competition with olive trees.
Soil water management	It is important to mow weeds and grasses during spring, before the starting of water competition with olive trees.

7.2 Increases in greenhouse gas emissions

Emissions of CO_2eq/kg of olives, calculated according to the Life Cycle Assessment (LCA) methodology, were 0.08 kg in the S_{mng} system and 0.11 kg in the C_{mng} system (Pergola *et al.*, 2013).

7.3 Decreases in production (food/fuel/feed/timber/fibre)

Reduction of olive production can occur if spontaneous cover crops are not promptly mowed before competing for water and nutrients with olive trees.

8. Recommendations before implementing the practice

It takes some time to have the first positive results, in terms of soil quality and olive yield after the conversion from C_{mng} to S_{mng}.

9. Potential barriers for adoption

Table 67. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Olive growing is often based on the application of traditional horticultural practices. These are practices handed down over time, and they often have no scientific and physiological basis. Therefore, it is hard to convince farmers to adopt new technologies.
Economic	Yes	Conversion to a sustainable system has some initial costs.
Institutional	Yes	Lack of specific legislation and low bureaucracy.
Knowledge	Yes	Conversion to a sustainable system requires the dissemination of technical and scientific knowledge to farmers.

Photo

SUSTAINABLE MANAGEMENT (S_{mng})

CONVENTIONAL MANAGEMENT (C_{mng})

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Photo 31. Comparison between the two different soil management types in the studied olive orchard

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17. Mediterranean savanna-like agrosilvopastoral grassland system in Spain, Italy and Portugal

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1. Related practices and hot-spot

Grassland diversification, Agrosilvopastoralism; Grasslands

2. Description of the case study

The typical Mediterranean savannah-like grassland system called *Dehesa* in Spain, *Montado* in Portugal and *Pascolo arborato* in Italy is a UNESCO protected (UNESCO, 2017) multifunctional agro-forestry system aggregating balanced and combined agricultural, livestock and forestry activities. This agrosilvopastoral system is mainly dominated by scattered evergreen oak trees (*Quercus suber, Q. ilex, Q. rotundifolia, Q. faginea, and Q. pyrenaica*) in association with pastures, and sometimes used for crops and/or fallows. In the Iberian Peninsula and the Mediterranean basin, this traditional system is adapted to the unpredictable Mediterranean climate (Moreno and Cubera, 2008) and the local edapho-climatic conditions, which are frequently dominated by shallow soils with low organic matter (Pinto-Correia, Ribeiro and Potes, 2013). Extensive livestock management (mostly beef cattle, sheep, goats and autochthone pig breeds, in mono or mixed systems) is responsible for the ecological features of this system. At a reduced stocking rate, a balance can be achieved between animal pressure and the territory conservation. Moreover, this ecosystem is critical for biodiversity protection because biodiversity-rich areas occur close to or even dependent on some agricultural activity (Pinho *et al.*, 2018).

Although livestock sector represents ~14.5 percent of all human GHG emissions, it is important to distinguish among the existing livestock farming systems when assessing animal production's climate responsibility. Due to the great capability of agrosilvopastoral grasslands to sequester CO_2, pastoral-based production closely represents a carbon (C) neutral system or can even mitigate GHGs (Llorente and Moreno, 2020).

3. Context of the case study

This system covers around 4 million hectares in central and south-western Iberian Peninsula and can also be found in other areas around the Mediterranean basin. The climate is typically Mediterranean, with drastic intra- and inter-annual climatic variability. Rainfall, ranging from 400 to 800 mm, concentrates in autumn and winter followed by a long hot and dries summer. The mean annual temperature ranges from 14 to 17°C. This ecosystem is usually found on shallow (< 50 cm) and acid soils originated from siliceous rocks, which are poor in nutrients (Pulido and Picardo, 2010). Adding to this, the Mediterranean climate determines a rapid organic matter (OM) mineralization leading to the loss of SOC (Cordovil, 2004).

4. Possibility of scaling up

In this ecosystem, livestock takes advantage of the forage resources by not only just comprising grassland but also trees, which are also used as a hydrological stress regulator for the underlying herbaceous stratum (Joffre *et al.*, 1999). Trees are used as a feed complement resource for livestock (e.g. acorns and small branches) and host a diversity of bird species and lichens and supply ecosystem services such as C sequestration, soil quality improvement, erosion prevention, nutrient cycling, water and thermal regime regulations, as well as favour soil biota, mycological heritage and biodiversity. Besides, it also offers cultural, landscape and hunting benefits

(Pinto-Correia *et al.*, 2013). So, in a climate change scenario this system represents a great adaptation strategy, potentially replicable to other parts of the world with similar conditions.

5. Impact on soil organic carbon stocks

There is still limited data on emissions from extensive livestock grazing systems in different types of grasslands. Thus, amount of compensation by the C sequestration capacity of the system by trees, plant biomass and soil organic matter is not available. Following the "soil saturation" concept, pasture soils initially poor in OM tend to have higher C sequestration rates than those of soils initially richer in OM (Llorente *et al.*, 2020; Table 68). Also, soil C storage capacity in this system is around 2.8 percent while the current average soil C content in the region is 1.7 percent or less, confirming the ability to capture and store more C in its soils.

Table 68. Evolution of soil organic carbon stocks of the three presented systems

Location	Climate zone	Soil type FAO (2015)	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Spain	Medi-terranean	Cambisol, Luvisol	72.0	0.83	22	0-20	In dehesa soils, C sequestration seems enhanced by the presence of cattle; F.	Llorente *et al.* (2020)
Sardinia, Italy		Cambisol	42.9	0.65-1.24	37		Values depend on stocking density and grassland management; F.	Francaviglia *et al.* (2017)
Portugal		Several types	0.45-1.91 %SOM	0.71-1.91	4		In montado soils, pasture improvement increases C sequestration and drought resistance; F. M.	Teixeira *et al.* (2011) Cordovil *et al.* (2020)

F: Field experiment, M: Modelling

6. Other benefits of the practice

6.1. Improvement of soil properties

This system protects soil erosion, balances water cycle and increases OM input, among other benefits. The presence of trees, as well as extensive livestock management with a proper stocking rate enhances SOM incorporation into the soils, improves biological activity, and contributes to close nutrient's cycles in the system. These benefits are further increased with the use of diverse pastures, where legume species are incorporated.

6.2 Minimization of threats to soil functions

Table 69. Soil threats

Soil threats	
Soil erosion	Trees and grassland help increase SOM and thereby improve soil structure and reduce soil erosion
Nutrient imbalance and cycles	Nutrient cycles are closed within the system, e.g. N fixation and OM mineralization.
Soil contamination / pollution	Diffuse manure spreading. SOM increased potential fosters soil buffer capacity.
Soil acidification	A good pasture and grassland management will reduce inorganic fertilization need, thus potentially reducing the risk of soil acidification from its application.
Soil biodiversity loss	The spread of manure and the activity of ruminants encourages the diversity of edaphic microorganisms. Diverse pasture and grassland maintain increased biodiversity.
Soil compaction	Low stocking rate and low cropping/soil tillage. These ideal livestock stocking rate depends on the animal, the climate and the type of soil.
Soil water management	Better water cycles balance and water regime. Improves soil structure, water infiltration and water retention through OM build-up.

6.3 Increases in production (e.g. food/fuel/feed/timber)

This multi-productive system includes the processing and fractionation of biomass for feed, food, energy (as firewood and charcoal) and other non-food applications such as cork production. This diversified production system shows a positive opportunity for grassland farmers and their communities.

6.4 Mitigation of and adaptation to climate change

In a climate change future scenario, agrosilvopastoral system represents an efficient mitigation and adaptation strategy, because they account for nearly zero balance between C sequestration and CO_2 equivalent emission of its animal-derived products. It has been reported that grass-fed cattle tend to generate higher enteric methane emissions than feed-fed cattle (Knapp *et al.*, 2019). These are not sufficiently captured through a single CO_2e footprint, indicating a non-significant variation between them under global warming potential (GWP_{100}) where non-grass fed systems generally appear more emissions efficient, and the 100-year global temperature potential (GTP_{100}), grass-fed beef had lower footprints (Lynch, 2019). However, extensive farming represents a relevant decrease in external inputs to the farm. Also, when considering the C sequestration in the agroecosystem linked to the extensive livestock, carbon footprint of animal production could be close to C neutrality (Llorente *et al.*, 2020).

6.5 Socio-economic benefits

The system provides opportunities to engage populations in rural areas through many related activities including sustainable agriculture, forest products, food and feed production, leisure and tourism activities among others. In contrast, intensive farming in similar areas is ending with tourism activities and sustainable agriculture due to the great environmental impact of that kind of farms such as bad smells, flies, or water pollution.

7. Potential drawbacks to the practice

7.1 Trade-offs with other soil threats

Table 70. Soil threats

Soil threats	
Soil erosion	Correct livestock stocking rates are important to avoid soil erosion.
Nutrient imbalance and cycles	Increased biodiversity and SOM promote nutrients cycling
Soil contamination / pollution	If the manure, or any other input, is contaminated this lead to increase soil pollution.
Soil biodiversity loss	When livestock is treated with antibiotics and dewormers the manure could have a negative effect in soil diversity. Stocking rates and grazing management may affect negatively.
Soil compaction	Correct livestock stocking rates are important to avoid soil compaction.
Soil water management	Better water infiltration and retention capacity occurs through increasing OM.

7.2 Increases in greenhouse gas emissions

Eldesouky *et al.* (2018) estimated GHG emissions ranging from 1.0 to 1.8 t CO_2eq/ha/year for Mediterranean grazing livestock, depending on farm size, management, and intensification. Llorente *et al.* (2020) estimated that *dehesa* ecosystem sequesters an average of 3.3 tCO_2eq/ha/year taking into account soils, trees and pasture. Therefore, livestock products derived from Mediterranean savannah-like agroecosystems should be considered as neutral or even negative.

7.3 Conflict with other practice(s) and tools to overcome barriers

The associated extensive livestock production is threatened by low-cost products of intensive farming, thus reducing competitiveness when the market does not pay for quality. Development of labelling systems linking livestock products with its ecosystem services could be a key tool to guarantee the conservation of agrosilvopastoral systems.

7.4 Other conflicts

Abandonment of land, population aging, and depopulation of the Mediterranean basin rural areas have a negative impact on the maintenance of these systems. Young generations show little attraction due to the low level of potential income. Overexploitation of the pastures and the forest and the lack of renewal of the woodland and trees diseases management is accelerating the decline of such systems and compromise their survival and sustainable management.

8. Recommendations before implementing the practice

Climate change impacts are linked to an increased vulnerability of trees to diseases. Oak decline has been occurring across Europe over the past decades due to malpractice, natural causes and uncontrolled diseases. The pseudo fungus oomycete *Phytophthora cinnamomiseria* is thought to be the main cause of holm oak decline (Ruiz Gómez *et al.*, 2019). *Platypus cylindrus* is an ambrosia beetle known to establish associations with six ambrosia pathogenic fungi, contributing to weaken the trees and leading to trees stand decline. The flathead oak borer *Coroebus undatus* F. (*Coleoptera*: *Buprestidae*) is another of the primary pests of cork oak in the Mediterranean region (Fürstenau*et al.*, 2014). Therefore, an integrated management including the use of biocontrol agents like Trichoderma, and the selection of resistant trees, is important to guarantee the sustainability of this ecosystem.

9. Potential barriers for adoption

Table 71. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Population aging, urbanization. Low potential income of the systems
Social	Yes	Rural areas abandonment.
Economic	Yes	Little incentives to maintain the appropriate tree density. Intensive farming products price to the market. Lack of certification.
Institutional	Yes	Not enough support.
Legal (Right to soil)	No	Heavy legal constraints to forest management.
Knowledge	Yes	More research is needed related to oaks' pests and diseases, and forest management factors that are responsible for forest decline.
Natural resource	No	Water stress from reduced precipitation driven by climate change impacts, increases trees vulnerability to pests and diseases.
Other	Yes	Historical overexploitation of the systems. Livestock density control and pasture management are key factors for the sustainability of this ecosystem.

Photos


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Photo 32. Showing savana-like agrosilvopastoral system. Cáceres, Spain, 2019

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18. Cover cropping in olive and vineyards (woody crops) in Spain

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1. Related practices

Cover cropping, Intercropping: Strip cropping

2. Description of the case study

Plant covers are used in the strips of woody crops to prevent erosion, to improve soil structure, and simultaneously to increase carbon content in the upper layers of soils. In this study cover crops were applied in central Spain, at the regional scale.

Plant covers can be made of spontaneous vegetation or can be sown e.g. with grasses or legumes. The species to be used are diverse, but native species and particularly those with shallow root systems and low water requirements should be used. In the case of cultivated plant cover, the seed rates vary, depending on the soil and climatic conditions; trials in central Spain, having less than 400 mm of rainfall, were performed with 40 to 100 kg of seeds per hectare. They should be sown at the beginning of winter, and mowed in early or mid-spring, depending on the rains of the year; the aim is preventing water competition with the main crop. Each year the management can be adapted to the weather conditions. The cut straw or harvest residues can be left on the ground, or if needed, can be used as fodder.

Spontaneous or natural vegetation used as plant cover should also be cut, and it is important not to delay the first mowing because natural vegetation is very efficient when using water resources and can seriously compete with the woody crop. In more humid areas, or in humid years, natural vegetation may need additional mowing during the spring. These assumptions were made: adapted species, shallow root system, limited seed rate, and mowing may prevent water competition with the woody crop.

3. Context of the case study

Different locations and different soils in Central Spain were used, but the climatic conditions were similar: less than 400 mm of annual rainfall and average temperatures around 14 °C. The soils of this region are basic (pH 8-8.5), with significant accumulations of lime or gypsum; they are shallow soils, the rooting depth is usually less than 50 cm.

The landscape of the south of Madrid is dominated by agricultural land. The more productive soils are limited to the level lands close to the rivers; the rolling and sloping areas with shallow soils are covered mainly by olive groves and vineyards. Finally, areas of shrub vegetation are associated with the tops of the hills. In the Madrid region, olive groves and vineyards are managed mostly by traditional and minimum tillage, and the use of cover cropping is testimonial, approximately 6 percent of olive groves and less than 2 percent of vineyards, including spontaneous and seeded covers. There is a high potential to increase the use of this practice.

4. Possibility of scaling up

In Spain, and also in other Mediterranean areas, cover cropping in woody crops is relatively frequent if annual rainfall exceeds 600 mm, but rare in drier environments. We have noticed a refusal to use cover cropping in this region with less than 400 mm; however, we demonstrated its feasibility, limited impact on production, and the benefits for soil protection, especially when soil slope is higher than 3 percent. Capacity building and policy measures to support farmers will allow the scaling up process.

5. Impact on soil organic carbon stocks

The SOC sequestration efficiency varies significantly between soils, climate, and depends on the amount and origin of carbon inputs. Different trials in vineyards (Photo 33) and olive groves (Photo 34) in the south of Madrid (Spain) using cover crops in the middle of the strips produced a significant increase of C stock. The data refer to topsoil, up to 10 cm depth, i.e. the arable layer of soil using minimum tillage. The additional C storage potential per year is compared to the minimum tillage or business as usual (BAU) described in the context of the case study. All references cited in Table 72 come from a warm temperate dry climate.

Table 72. Evolution of SOC stocks in different trials in vineyards and olive groves in the south of Madrid, Spain

Location	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	More information	Reference
Belmonte de Tajo	Calcisol Hypercalcic	10.2	1.3	2	Vineyard Cover: Purple false brome (*Brachypodium distachyon)*	Ruiz-Colmenero, Bienes and Marques (2011)
	Calcisol Hypercalcic	10.2	1.9		Vineyard Cover: spontaneous vegetation.	
Villaconejos	Calcisol Hypocalcic	4.6	2.6		Vineyard Cover: barley (*Hordeum vulgare*)	
Campo Real	Luvisol Calcic	8.0	1.0	4	Vineyard Cover: Purple false brome	Ruiz-Colmenero *et al.* (2013)
Colmenar de Oreja	Haplic Gypsisol	10.9	0.9	3	Olive grove Cover: Purple false brome	Sastre *et al.* (2018)

6. Other benefits of the practice

6.1. Improvement of soil properties

Plant covers produce a cascade of physical, chemical, and biological changes that may improve soil properties.

Physical properties

Water infiltration with cover crops is improved and maintained over the year thanks to the creation of higher soil porosity by the root systems; for instance, cover crops showed in average 25 cm/h of infiltration compared to 13 cm/h in tillage treatments. Importantly, after two consecutive research projects, that is, nine years of plant covers with purple false brome, there was an increase in soil water holding capacity from 11 to 13 percent in one of these vineyards (García-Díaz *et al.*, 2018). Both increases, water infiltration and water holding capacity, may help to counterbalance the plant cover's water consumption.

Soil aggregate stability improved no matter the species of the cover crop used to protect soils in these semi-arid environments (Sastre *et al.*, 2018; Ruiz-Colmenero *et al.*, 2013).

One of the effects of cover crops is the increase of soil bulk density for example from 1.3 to 1.4 g/cm^3, however, this increase does not influence water infiltration which can even double the infiltration found with minimum tillage (García-Díaz *et al.*, 2018).

Chemical properties:

Soil nitrogen increased from 0.64 t/ha to 0.72 t/ha after three years of purple false brome in olive groves cultivated in gypsiferous soils (Sastre *et al.*, 2018)

Biological properties:

Biological changes induced by plant covers in soils can be positive or negative considering the possibility of plagues spread. Plant covers involve a microclimate modification, an increase of resources, and available niches that in turn, lead to an increase of biodiversity. There is a significant increase in the mass of roots in the topsoil, up to 30 cm (Ruiz-Colmenero *et al.*, 2013). This way, the roots of vegetation produce metabolites that influence directly the composition and biomass of soil microorganisms, promoting the development of mycorrhizal fungi of great interest for the woody plantation. Plant covers are more effective at augmenting organic carbon content and sustaining higher potential microbial respiration and carbon from microbial biomass than tillage.

6.2 On minimizing soil threats

Table 73. Soil threats

Soil threats	
Soil erosion	In this region, minimum tillage in the strips of sloping vineyards produced 6 t/ha/year of soil erosion, compared to approximately 1 t/ha with cover crops (Ruiz-Colmenero *et al.*, 2013). Similar figures were found in olive groves; minimum tillage produced 7 t/ha/year, and different cover crops reduced this rate from 40 to 80% (Sastre *et al.*, 2017).
Nutrient imbalance and cycles	Roots of cover crops are one of the main sources of carbon and nitrogen in soils; root exudates contribute to the stabilization of soil C and N in the upper 5 cm (Sastre *et al.*, 2018).
Soil biodiversity loss	Biological activity and nutrient cycling promoted by roots and microorganisms facilitate the stability of soil aggregates, apart from its importance to prevent soil erosion, stable aggregates enable organic carbon storage. Compared to tillage, soils with cover cropping experience improvements in nematodes and fungi (IMIDRA Annual Report, 2017).
Soil compaction	Minimum tillage practices have short-term effects on soil porosity, and after several rainfalls, soils tend to compact the first millimeters soil surface and produce crusts. The cover crops decrease the drop chance to impact directly in the soil, reducing its susceptibility to crusting. Soils with crusts show higher and rapid runoff compared to soils with cover crops in vineyards (Marques *et al.*, 2020).

Soil threats	
Soil water management	In medium-term experiments cover crops have demonstrated a positive effect on water holding capacity thanks to the improvement of soil structure and SOC content (García-Díaz *et al.*, 2018).

6.3 Mitigation of and adaptation to climate change

Several aspects of this practice can help to adaptation and mitigation to climate change. Mitigation is achieved by the possibility to increase SOC sequestration in soils and in living biomass of vegetation covers. Adaptation is achieved when soils, in better conditions, are able to hold more water and nutrients than soils degraded by conventional tillage; the shadow provided by vegetation cover mitigates evaporation and organic matter decomposition in soils.

6.4 Socio-economic benefits

In conversations with farmers, they admit that the use of cover cropping reduces the fuel consumption, as there are fewer tractor passes in vineyards or olive groves with strips covered by vegetation. Because of less use of tractor and fuel, farmers save money and time, which is of special importance for them. Farmers can also get another income or benefit from the same field if they use the mowed cover cropping, for example providing forage. The growing environmental concern of consumers can lead to an increasing willingness to pay more for sustainable products like wine or olive oil from protected soils.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 74. Soil threats

Soil threats	
Nutrient imbalance and cycles	Fertilization and mowing are needed to avoid competition with the main woody crop. Nitrogen and phosphorus deficiencies may be noticed, especially in soils with high pH (Ruiz-Colmenero, Bienes and Marques, 2011).
Soil compaction	There is a slight increase in bulk density in soils managed with cover crops, however, it does not influence water infiltration (García-Díaz *et al.*, 2018). The unwanted soil

Soil threats	
	compaction can be concealed if minimum tillage is performed each 4 to 5 years, as is recommended by several authors and farmers. Medium and long-term experiments, lasting more than 4 to 5 years, will be useful to demonstrate the long-term effects of cover crops to revert the initial soil compaction.
Soil water management	In drylands, cover crops must be carefully managed due to water shortages. Frequent mowing and support irrigation may be needed. Young vineyards can significantly reduce grape production during dry spells (Ruiz-Colmenero, Bienes and Marques, 2011).

7.2 Conflict with other practice(s)

Cover cropping might pose a conflict with conventional tillage. In conversations with farmers who apply cover cropping, we acknowledged that other farmers who use tillage to manage land, might complain arguing that adjacent plots with vegetation cover are the source of plagues. This is due to the lack of knowledge about the benefits of this practice, as research demonstrates that the effect is the opposite, as cover cropping practices may provide also biological pest and disease control.

7.3 Decreases in production (food/fuel/feed/timber/fibre)

In vineyards, production declines have been reported during the first years of plant cover implementation, for example, grape production can decrease between 10 and 50 percent in dry years and young vineyards, although the old vines seem to be more resistant to water competition (Ruiz-Colmenero, Bienes and Marques, 2011). The influence of plant cover on grape yield depends mainly on the yearly weather conditions and can be mitigated by the redistribution of vine root system exploring deeper soil layers (Celette, Gaudin and Gary, 2008). In olive groves, only a slight decrease was found if a permanent cover was used as cover cropping, other species did not change the yield per tree (IMIDRA Annual Report, 2017).

8. Recommendations before implementing the practice

In semi-arid environments cover crops cannot be installed during the first (three to five) years of vineyard or olive tree plantations, as the water competition can reduce the development of young woody crops (Ruiz-Colmenero, Bienes and Marques, 2011) unless irrigation is available.

An initial test of different species is strongly recommended in small plots of the farm, as not all the species show the same ability to adapt to different soil or climatic conditions. For example, legumes, as cover crops are especially interesting if there is a need to improve nitrogen fixation, however, in several experiments, lentils did not thrive in gypsiferous soils (Ruiz-Colmenero, Bienes and Marques, 2011), or sainfoin (*Onobrychis viciifolia*) did not increase nitrogen compared to other grasses (Sastre *et al.*, 2018). Therefore, start small, and start simple are wise recommendations.

9. Potential barriers for adoption

Table 75. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	This practice is site-specific, soil characteristics and above all, water availability can jeopardize the application (Marques *et al.*, 2015).
Cultural	Yes	Knowledge usually is transmitted from father to son, or from pears, so tradition, tillage, in this case, is difficult to be changed (Barbero-Sierra *et al.*, 2016).
Social	Yes	Similarly, plots with cover crops are usually seen by the local community as plots no managed, and farmers are then considered lazy or bad farmers (Sastre *et al.*, 2017).
Economic	Yes	The costs of seeds and the decrease in production are reasons to impede implementation (Marques *et al.*, 2015). Land tenure based on small and scattered plots increase costs and also adversely affects adoption (Barbero-Sierra *et al.*, 2016).
Institutional	Yes	Conflict with certain aids or subsidies based on the evidence of current land working. Cover crops may be wrongly identified from satellites as abandoned lands, and farmers do not perceive subsidies (information from open interviews with farmers, not checked). Institutional support has been identified by farmers as an important factor to adopt this technique (Barbero-Sierra *et al.*, 2016).
Knowledge	Yes	An important percentage or farmers declare the need to be trained to adopt cover crops (Marques *et al.*, 2015).

Photos

Photo 33. Different cover crops in sloping rainfed vineyards in the province of Madrid (Spain)
Soils with barley (upper left), spontaneous vegetation (upper right), and purple false from (down).

Photo 34. Rainfed olive grove in Madrid (Finca La Chimenea, IMIDRA) with barley (left) and purple false brown (right) in 2014
Drip irrigation is used only in case of extreme drought

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19. Irrigation and SOC sequestration in the region of Navarre in Spain

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1. Related practices and hot-spot

Adequate irrigation practices, organic agriculture, crop rotations; Drylands

2. Description of the case study

The project REGADIOX, funded by the European Commission LIFE Program was based on the establishment of a regional-scale network of representative agricultural plots in three irrigation districts in Navarre (NE Spain). The project allowed for a rational evaluation of soil organic C (SOC) sequestration and greenhouse gases (GHG) emissions balances by using paired comparisons in terms of soil characteristics in irrigated vs rainfed plots. The results showed a clear influence of irrigation in soil condition, arising from greater SOC storage. The net effect was however modulated by soil characteristics and management practices, in so far as the different agricultural strategies did have different potential to sequester SOC and/or reduce GHG emissions. While permanent crops with green cover (which was possible thanks to irrigation) or semi-permanent crops as alfalfa were win-win strategies with positive C balances, intensive systems with two crops per year, although they also contributed to SOC gains, represented increased GHG emissions.

The observed changes in SOC associated to irrigation with different managements also showed that irrigation adoption can alter the soils' capacity to provide key ecosystem services beyond biomass production, as changes in soils properties related to SOC, such as water-holding capacity or soil erodibility were also observed. These changes were, however, not straightforward and varied depending on soil type, climate and time under irrigation.

3. Context of the case study

The project was led by a farmer's union (UAGN-Fundagro) in the region of Navarre (NE Spain), together with extensionists from the regional Agricultural Extension Institute (INTIA) and researchers from UPNA.

The region has a marked North-South rainfall gradient with average annual rainfall ranging from 380 to 505 mm and reference evapotranspiration (ET_o) of 1 000 to 1 100 mm, which makes agriculture strongly dependent on irrigation in the Southern part of the region.

Soils in the irrigated area are mostly derived from sedimentary rocks and quaternary alluvial deposits and terraces. Most are calcareous (Calcisols, Cambisols) and display high pH and carbonates concentration in the tilled layer. Irrigation is used for producing a variety of crops, from permanent (olive trees, vineyards) to semi-permanent lays (alfalfa (*Medicago sativa*), cereals (wheat (*Triticum aestivum*) and maize (*Zea mays*) and horticultural crops (tomatoes (*Lycopersicon esculentum*) and legumes). The project selected representative irrigation districts and plots in the whole irrigated area of the region and had therefore a regional perspective.

3. Possibility of scaling up

The study could be scaled-up to other irrigated areas in the Mediterranean region.

4. Impact on soil organic carbon stocks

Table 76. Evolution of SOC stocks after different years of irrigation and soil cover in the region of Navarre, Spain

Location	Climate zone	Soil type (Soil Taxonomy, 2014)	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years of irrigation)	Cropping system	Reference
1. Non-permanent crops[1]							
Miranda de Arga	MAP/PET*: 0.59	*Typic Calcixerept*	43.9±4.00	2.08 ± 1.14	6	Irrigated annual cropping	Antón *et al.* (2019)
				3.20 ± 1.82		Irrigated alfalfa	
Funes	MAP/PET: 0.52	*Xeric Haplocalcid*	35.4±0.73	0.84 ± 0.11	13	Irrigated annual cropping	

Location	Climate zone	Soil type (Soil Taxonomy, 2014)	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years of irrigation)	Cropping system	Reference
Valtierra	MAP/PET: 0.51	*Xeric Haplocalcid*	57.3±4.21	0.86 ± 0.68	20	Rainfed organic	
				2.80 ± 0.69		Irrigated annual cropping	
2. Permanent crops[2]							
Fontellas	MAP/PET: 0.49	*Typic Calcixerept*	50.2±17.7	2.92 ± 0.86	16	Irrigated grass cover (olives)	Mendioroz *et al.* (2017)
Cascante	MAP/PET: 0.49	*Xeric Calcigypsid*	30.9±2.20	3.23 ± 0.22	9	Irrigated grass cover (grapevines)	

Climate is Warm Temperate Dry according to IPCC (2006)

Measurements were made on 0-30 cm depth

[1] Baseline is rainfed cereal cropping on the same soil unit

[2] Baseline is the same crop (irrigated) with bare soil

*MAP: Mean annual precipitation; PET: Potential Evapotranspiration

5. Other benefits of the practice

5.1. Improvement of soil properties

Positive changes in soil properties were observed in some cases, associated with SOC gains. Significant gains in the water-holding capacity in the upper 30 cm of the soil were for example observed in Miranda de Arga in the irrigated systems (642 L/m^2 on average) compared to dryland cultivation (533 L/m^2). No differences were observed in bulk density, most likely because tillage was conventional in all the studied agrosystems.

5.2 Minimization of threats to soil functions

Table 77. Soil threats

Soil threats	
Soil erosion	Measured erodibility reduced in some cases (Miranda de Arga) with irrigation vs. dryland (Antón *et al.*, 2019).
Soil biodiversity loss	Site-dependent response of soil microbial abundance and diversity (Antón *et al.*, 2019).
Soil water management	Irrigation implied a sufficient supply granting profitable yields. In some cases (Miranda de Arga), irrigation increased the soil water-holding capacity. In others (Valtierra), the opposite was observed (Antón *et al.*, 2019).

5.3 Increases in production (e.g. food/fuel/feed/timber)

Biomass production was between 2.4 and 3.4 times higher in the irrigated systems than in rainfed cereal cropping on the same soil units (Antón *et al.*, 2019).

5.4 Mitigation of and adaptation to climate change

GHG gases emissions were measured and displayed very variable results both when comparing irrigated and non-irrigated systems, and between irrigated systems (Figure 18).

In terms of adaptation, irrigated systems performed better in terms of yield than rainfed crops (less interannual variability and of course higher productivity).

5.5 Socio-economic benefits

The introduction of irrigation implies more stable and profitable yields. Within irrigated systems, horticultural crops, olive trees and grapevines are the most profitable. This means that economic (income) and environmental (SOC gain) drivers did not always match (Antón *et al.*, 2019).

6. Potential drawbacks to the practice

6.1 Tradeoffs with other threats to soil functions

Table 78. Soil threats

Soil threats	
Soil erosion	Sprinkler irrigation can cause erosion depending on crop stage and irrigation intensity.
Nutrient imbalance and cycles	Irrigation implies higher fertilization and increased leaching than rainfed agriculture.
Soil salinization and alkalinization	A risk if drainage is not good.
Soil water management	Efficient water use needed for reducing risks associated with irrigation.

6.2 Increases in greenhouse gas emissions

Information on net balances (emissions vs SOC sequestration) are summarized in Figure 18.

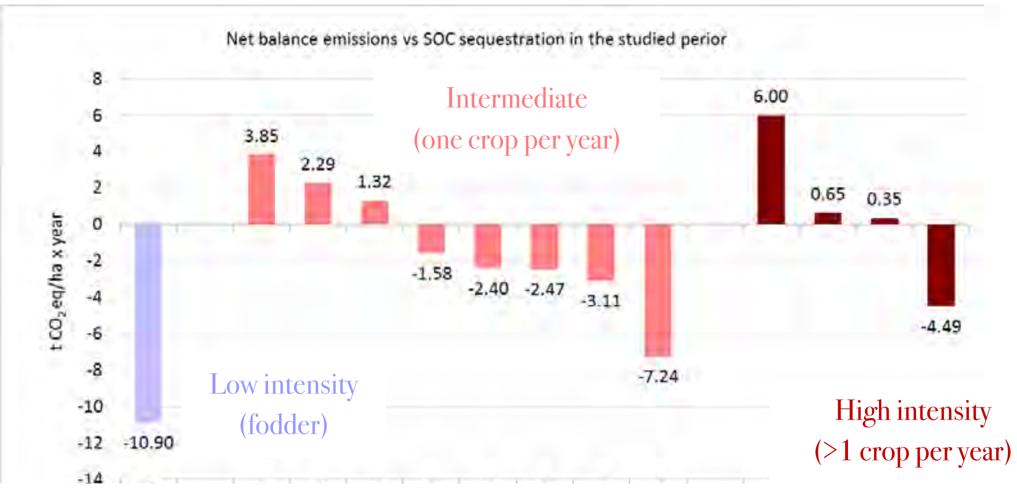

Figure 18. Net balance between GHG emissions and SOC sequestration in the study period in the different irrigated plots studied Positive values indicate net emissions. Negative values indicate mitigation by effective C sequestration

As shown in the figure, low intensity irrigated systems (alfalfa fodder) had the clearest benefit in climate change mitigation, as emissions were low (no N fertilization) and C sequestration high. Very intense systems, with more than one crop per year, although very effective in increasing SOC stocks compared to non-irrigated soil, also had high emissions, mostly associated to N fertilization, with a positive net balance.

Intermediate irrigated agro-systems (one crop per year) displayed the highest variability depending on soil, climate conditions and time since the adoption of irrigation.

7. Potential barriers for adoption

Table 79. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	All soils cannot be irrigated.
Cultural	Yes	Changing from rainfed to irrigated agriculture is not easy.
Social	Yes	
Economic	Yes	Irrigation can be costly.
Institutional	Yes	Irrigation needs public investment.
Knowledge	Yes	Training needed for farmers adopting irrigation.
Natural resource	Yes	Water is limited.

Reference and more information (In Spanish):

https://life-regadiox.es/wp-content/uploads/2016/12/EvaluacionSocioeconomicaRegadiox_fin.pdf

Photo

Photo 35. Picture of a "boundary" area between newly irrigated land (right of the sprinkler) and the rainfed area on the same soil unit (left of the sprinkler), in winter

Winter wheat grows in the non-irrigated area on the left. Maize is grown in the irrigated area on the right (see maize stover still not incorporated into the soil at the front and deep inversion tillage to incorporate crop residues at the back). Growing maize in the area would be impossible without irrigation. Miranda de Arga, Navarre, Spain. January, 2014.

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20. Application of mulching in subtropical orchards in Granada, Spain

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1. Related practices and hot-spot

No-till, terracing, organic mulch, cover cropping; Drylands

2. Description of the case study

The geographical extension of subtropical crops has been increasing in the Mediterranean area in the recent years. These crops are characterized by their disposition in terraces due to the geographical location and proximity to coastal zones, apart from producing large amounts of pruning waste, which can favour the emission of CO_2 including their burning. Being chipped and applied on soil surface, these prunings can improve soil quality and have a great impact on carbon storage (Jiménez *et al.*, 2016). This is especially valuable in a hot and dry climate which is per se favoring mineralization, impeding humification, limiting crop growth and complicating land recovery after degradation (Pardo *et al.*, 2017).

For five years we conducted an experiment trial in which we tested the application of pruning residues as mulch in three different subtropical orchards. The experimental design consisted in the application of prunings from avocado (*Persea americana*), cherimoya (*Annona cherimola*) and mango (*Mangifera indica*) trees, placed on the surface soil underneath their correspondent trees, as well as garden cuttings from the green areas surrounding the municipality. Mulching effect was assessed with a focus on chemical fractionation of soil organic carbon, attending to the diverse stabilization mechanisms that may later differ into different carbon pools. Furthermore, other physicochemical properties (bulk density, soil humidity, cation exchange capacity) were evaluated.

3. Context of the case study

The study was conducted in the Experimental Farm "El Zahorí" (36°45′54.2″N, 3°39′55.0″W), located in the municipality of Almuñécar (Granada, Southern Spain) at the elevation of 180 m a.s.l. This research has been financially supported by the Spanish Ministry of Economy and Competitiveness (Project CGL-2013-46665-R) and the European Regional Development Fund (ERDF).

The predominant climate of the study area is Warm Temperate Dry (IPCC, 2019) with an average annual temperature of 18.3°C and average rainfall of 334 mm. Soil in this area developed on weathered schists and is classified as Eutric Escalic Anthrosol (IUSS Working Group WRB, 2015). In 2013 soil samplings revealed a sandy loam soil texture, with gravels being frequent in depth and a neutral to slightly alkaline pH (7 – 8.3). Selected crops to carry out the trial were: mango (*Mangifera indica* L.), avocado (*Persea americana* Mill.) and cherimoya (*Annona cherimola* Mill.). Orchards were established in monospecific patches on terraces, facing the sea in different orientations. All crops require individual management, concerning pruning intensity, irrigation and fertilization (via fertigation). Furthermore, the general management includes continuous ground cover vegetation and two annual mowing events. Treatments were applied on tree-pairs, separated by one untreated tree. The experiment started in 2013 with the first mulch application, following a complete randomized block design where prunings were applied annually.

4. Possibility of scaling up

The results from this project are intended to be extensively applied in other agroecosystems such as olive groves. These research outcomes aim to be successfully applied in other crops not necessarily disposed in terraces. Apart from the parameters evaluated and presented along this document, we encourage further research focused on microbial population, including enzymatic activities related with the C and N cycles at different times of the year, as well as basal and field respiration.

5. Impact on soil organic carbon stocks

Table 80 summarizes the evolution of SOC stocks in the 5-year study. The baseline SOC was calculated 25, 15 and 10 years after orchard establishment in avocado, cherimoya and mango respectively.

Table 80. Evolution of SOC stocks in the 5-year study at "El Zahorí" farm, located in Almuñécar, Granada (SE, Spain)

Treatment	Baseline C stock in 2013 (tC/ha) [mean± SE1]	Additional SOC stock after 5 years (tC/ha/yr) [mean± SE4]
Avocado with prunings	22.34 ± 2.49	1.69 ± 0.38
Cherimoya with prunings	11.15 ± 4.5	1.47 ± 0.44
Mango with prunings	8.22 ± 0.54	1.37 ± 0.25
Avocado with garden-cuttings	18.83 ± 2.56	3.27 ± 1.25
Cherimoya with garden-cuttings	6.95 ± 2.03	2.88 ± 0.5
Mango with garden-cuttings	6.69 ± 1.58	1.83 ± 0.42

Source: Adapted from Hoppe (2019) and Márquez-San-Emeterio et al. (2017a)

It summarizes the evolution of SOC stocks in the 5-year study. The baseline SOC was calculated 25, 15 and 10 years after orchard establishment in avocado, cherimoya and mango respectively. Climate is warm temperate fry according to the IPCC (2019). Soils are Eutric Escalic Anthrosol (IUSS Working Group WRB, 2015). Measurements were made on 0-4 cm depth

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[4] SE=SD/$\sqrt{n}$

6. Other benefits of the practice

6.1. Improvement of soil properties

Physical properties

Bulk density was reduced significantly after four years of mulching with pruning residues inside the avocado orchard. In 2013 the average bulk density of fine earth was 1.23 g/cm^3, while it was 1.14 g/cm^3 in 2017 as a result of an elevated SOC stock. All crops mulched with garden cuttings show significant differences in bulk density of fine earth after four years. Average bulk density decreased from 1.35 to 1.09 g/cm^3, from 1.55 to 1.38 g/cm^3 and from 1.52 to 1.41 g/cm^3 for avocado, cherimoya and mango orchard plots, respectively. These bulk densities were used to determinate calculate equivalent mass SOC stocks.

Chemical properties

Increased soil nutrients content (nitrogen and potassium) under pruning (Reyes-Martín *et al.*, 2020).

Biological properties:

It was showed in 2017 that the oribatid mite community under all prunings was numerically higher and more complex in terms of diversity index than those in their respective controls (Márquez-San-Emeterio *et al.*, 2017b).

6.2 Minimization of threats to soil functions

Table 81. Soil threats

Soil threats	
Soil erosion	The application of mulching and other organic coverages has proved to strongly improve soil aggregation and moisture storage. It also serves as physical barrier against evapotranspiration losses from soil, increasing infiltration and lowering runoff.
Nutrient imbalance and cycles	Preliminary results about the biochemical characterization of applied mulch showed that its application significantly increased the nutrient content in soils under pruning (Reyes-Martín *et al.*, 2020).
Soil biodiversity loss	Previous studies within this project evaluated the mesofauna community of Oribatida individuals. These results showed that the oribatid mite community under all prunings was numerically higher and more complex in terms of diversity index than those in their respective controls (Márquez-San-Emeterio *et al.*, 2017b).

Soil threats	
Soil water management	Use of mulching and other plant covers in terrace crops has optimized the use of irrigation water by increasing contact surface within the soil-water phase, as well as minimized excessive water runoff and, therefore, reduced socio-economic impact (Durán-Zuazo *et al.*, 2013; recent data not published).

6.3 On provision services

Not considered in the study.

6.4 Mitigation of and adaptation to climate change

Adopting pruning application avoids 0.13 t CO_2eq/ha/yr which would be set free by conventional burning of wood residues (based on formulas in Akagi *et al.*, 2011). However, additional fuel usage for wood shredding leads to emissions of 0.11 t CO_2eq/ha/yr (Dones *et al.*, 2007).

Additionally, the practice allows for reduction of mineral fertilizers due to additional plant material input. Present fertilization scheme leads to 9.95, 6.95 and 6.3 t CO_2eq/ha/yr in avocado, cherimoya and mango, respectively (Bouwman, Boumans and Batjes, 2002; Ecoinvent Centre, 2007).

6.5 Socio-economic benefits

Cost-effective discharge of garden cuttings for municipalities or other responsible bodies. Major return (pruning residues) and input (garden cuttings) of organic matter leads to an appropriate use and reduction of industrial fertilizers (Ye *et al.*, 2020).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 82. Soil threats

Soil threats	
Nutrient imbalance and cycles	The application of external prunings (those from gardens) could result in a significant nutrient imbalance that may alter soil physicochemical properties such pH and cation-exchange capacity (CEC). Benito *et al.* (2006) reported some of these changes due to the application of composted pruning material.
Soil contamination / pollution	An external source of mulch material, in this case garden pruning, can cause soil contamination issues due to the appearance of pathogens and chemical traceability of fertilizers, if not treated prior to its application.

7.2 Decreases in production (food/fuel/feed/timber/fibre)

Despite the positive effects of mulch on soil, which consequently improves crop conditions, no significant change of the nutrient concentration of fruits (cherimoya) could be observed over the study period. For more information, we recently published an article in which mulch application and potential nutritional changes in cherimoya fruit are discussed (García-Carmona *et al.*, 2020).

8. Recommendations before implementing the practice

We highly recommend pre-treating of only those cuttings coming from garden areas, due to their complexity and diverse origin. This plant material may be contaminated by herbicides and/or pesticides. This pre-treatment could be made by a conventional composting process, which application has been effectively tested in other case studies to remove any pathogen or pollution from chemical treatments (Benito *et al.*, 2006).

9. Potential barriers for adoption

Table 83. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	Non applicable in heavily inclined terrain without terraces due to the physical instability of prunings applied on the soil surface.
Cultural	Yes	In collaboration with institutions (i.e. city hall) and other research centers (Andalusian Institute of Agricultural and Fisheries Research and Training, *IFAPA*; Spanish Council for Research, *CSIC*), the organization of short courses, workshops and other events could be possible, covering all types of audience (farmers, stakeholders and decision-makers, internship students, etc.).
Economic	Yes	It may entail initial investment for purchasing shredding machines, in addition to an additional effort for shredding and distribution of wood chips.
Knowledge	Yes	Lack of experience on the practice of this technique in these areas.

Photos


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Photo 36. Shredding machine put into operation after crop pruning season in 2017. Almuñécar, Spain


© Tobias Hoppe

Photo 37. Avocado tree in terraced terrain with mulched soil in January 2018. Almuñécar, Spain


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Photo 38. Soil sampling after the annual replace of the mulching bags in 2016. Almuñécar, Spain

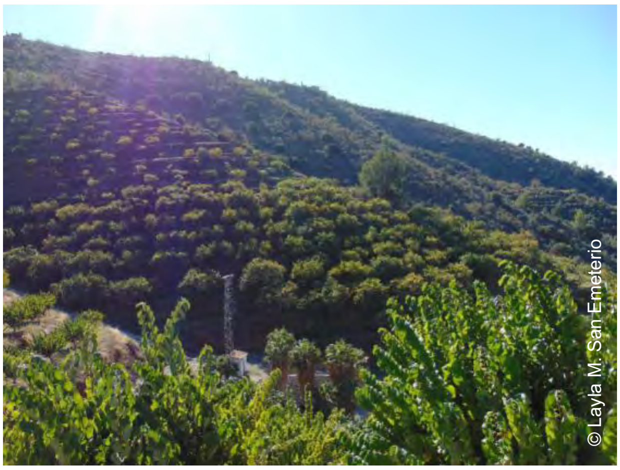
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Photo 39. Subtropical crop disposition in terraces, located in the experimental farm in 2016. Almuñécar, Spain

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21. Reduced tillage frequency and no-till to allow ground covers and seeding cover crops in rainfed almond fields, Spain

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1. Related practices and hot-spot

No-till, Reduced tillage, cover cropping, organic agriculture; Drylands

2. Description of the case study

These agricultural practices consist of reducing tillage frequency (twice per year) or halting tillage compared to conventional tillage (≥ four times per year) in two organic rainfed almond (*Prunus dulcis* Mill.) orchards under semiarid conditions. The aim is to protect soil against erosion and increase its organic matter content in the 7 to 10-meter-wide strips between the almond trees by allowing the establishment of a native plant cover (i.e. ground covers) or by seeding different varieties of legumes and cereals (i.e. green manure). The green manure consists of seeding a mixture of common vetch (*Vicia sativa* L.) and oat (*Avena sativa* L.) in a 3:1 ratio at 150 kg/ha in early fall to provide a cover crop during winter, but different varieties of legumes and grasses can be combined in order to increase species diversification. Given the water scarcity of this region, species with shallow root systems and low water requirements are desirable (e.g. *Vicia ervilia* W.). Early termination of ground covers and green manure is appropriate in this region where rainfall amount is relatively low (300 mm/yr) to avoid competition for water with the main crop. Generally, both types of cover crops are cut in early- or mid-spring when a significant amount of plant biomass is present (although management can be adapted to each year weather conditions), after which plant residues are left on the ground as mulching (in no tillage systems) or incorporated into the soil by chisel ploughing to 15-20 cm depth (in reduced tillage systems). In our study case, the effect of shifting from conventional tillage to reduced tillage, reduced tillage plus green manure, and no tillage, on soil carbon sequestration, soil CO_2 emission rates, and crop yields will be reported.

3. Context of the case study

The study took place in two calcareous arid and semiarid sites of the south of Spain, at about 50 km Est of Murcia (site 1: 38°3′15″ N, 1°46′12″ W; 633 m a.s.l; site 2: 37°51′59″ N, 1°43′11″ W; 839 m a.s.l.).

4. Possibility of scaling up

These agricultural practices can be implemented in rainfed and irrigated woody-crops growing worldwide.

5. Impact on soil organic carbon stocks

Soil samples were collected in the rows between almond trees following crop harvest in November 2018, ten years after the management practices were implemented. Four paired undisturbed (core of 100 cm^3 volume) and disturbed soil samples were collected for each management treatment, for bulk density estimations and organic carbon analyses, respectively. Soil organic carbon stock (t/ha) was computed as a product of soil organic C concentration, bulk density and depth for each sampling point (Table 84).

Table 84. Evolution of SOC stocks in Almond trees production in South Spain after 10 years of reduced tillage and cover cropping

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	More information	Reference
Spain	Warm temperate dry	Calcisol	42.23 ± 9.24 (n = 12)	1	10	Shift from conventional to reduced tillage at 20 cm depth	unpublished
			25.17 ± 2.8 (n = 12)	0.33		Shift from reduced to no tillage at 15 cm depth	

6. Other benefits of the practice

6.1. Improvement of soil properties

An improvement on biophysical properties, such as soil structure (aggregate stability) and soil water infiltration capacity (when no tillage is applied) was observed with decreasing tillage frequency (Almagro *et al.*, 2016; Almagro *et al.*, 2017; Martínez-Mena *et al.*, in press).

6.2 Minimization of threats to soil functions

Table 85. Soil threats

Soil threats	
Soil erosion	The plant covers in the strips between the almond trees reduced soil erosion rates and the associated carbon and nutrient mobilized by this process by 60-80% compared to conventional tillage (Martínez-Mena *et al.*, 2020).
Nutrient imbalance and cycles	Improvement of nitrogen availability under green manure (Martínez-Mena *et al.*, in press) and reduction of nutrient losses by erosion in all reduced tillage systems (Martínez-Mena *et al.*, 2020).
Soil water management	Reducing tillage intensity increased field available water content (Almagro *et al.*, 2016).

6.3 Increases in production (e.g. food/fuel/feed/timber)

After 10 years, no differences in crop yields between conventional and reduced tillage systems were observed. Mean values ranged from 40 to 321 kg/ha under conventional tillage and from 30 to 311 kg/ha under reduced tillage depending on the farm. However, when conventional tillage was converted to no tillage crop yields decreased by 73 percent (Martin-Gorriz *et al.*, 2020). This probably occurred because soil compaction under no tillage increased year after year, hampering organic matter mineralization and nitrogen availability for the main crop. Our results suggest that growing organic woody crops under rainfed semiarid conditions might not be compatible with no tillage practices when no fertilizers are applied, as it is our case, particularly in soils with high-carbonate contents and impoverished in organic matter and nutrients (Martínez-Mena *et al.*, in press). Therefore, tillage operations should be performed occasionally (i.e. once every 4-5 years) to allow soil aeration and decompaction, or no tillage should be combined with other practices, such as organic nitrogen fertilization.

6.4 Mitigation of and adaptation to climate change

No differences in soil CO_2 emissions were observed between tillage treatments (Almagro *et al.*, 2017), and N_2O and CH_4 emissions are expected to be negligible compared to the CO_2 ones in these organic rainfed farming systems (Sánchez-García *et al.*, 2016). On the other hand, the response of soil CO_2 flux to soil temperature and moisture was buffered by the plant covers in reduced tillage systems, making covered soils more resilient to extreme rainfall events, droughts, and warming, than bare soils (under conventional tillage; Almagro *et al.*, 2017). Furthermore, the effectiveness of these agricultural practices in controlling soil erosion and carbon and nutrient losses is higher during extreme erosive events (Martínez-Mena *et al.*, 2020), which are forecasted to increase under climate change scenarios.

6.5 Socio-economic benefits

Reduced tillage lowered the GHG emissions and improved the ratio of profit/GHG emissions with respect to conventional tillage, resulting in the best strategy for almond producers and the sustainability of land in our study case (Martin-Gorriz *et al.*, 2020). On the other hand, reduced tillage combined with green manure increased the GHG emissions from farm operations and reduced the ratio of profit/GHG emissions as a consequence of using seeds. Nevertheless, adding green manure becomes more positive when other socio-economic benefits and externalities (i.e. ecosystem services) are considered, such as the fact that: i) crop yields increase in the long-term (Martínez-Mena *et al.*, in press); ii) reducing soil organic matter and nutrient losses (indirect costs) by preventing soil erosion (Martínez-Mena *et al.*, 2020); and iii) maintaining soil fertility and health condition (Almagro *et al.*, 2017). Although no tillage (without fertilizer application) provided the lowest GHG emissions, yields were significantly reduced, and consequently, this practice is very close of being economically unfeasible, even with subsidies (Martin-Gorriz *et al.*, 2020).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 86. Soil threats

Soil threats	
Nutrient imbalance and cycles	Although soil nutrient balance and cycles can improve, competition for nutrients with the main crop can also occur (Martínez-Mena *et al.*, 2013).
Soil compaction	Increased when passing from reduced tillage to zero tillage (Martínez-Mena *et al.*, 2013).

Soil threats	
Soil water management	Competition for water with the main crop can be promoted, especially in dry years (Martínez-Mena *et al.*, 2013).

7.2 Increases in greenhouse gas emissions

Since no differences in soil CO_2 emissions were observed between tillage systems, and N_2O and CH_4 emissions are expected to be negligible compared to the CO_2 ones in organic rainfed farming systems, the net GHG balance is equal to the soil C sequestration rates provided in Section 4.

7.3 Decreases in production (e.g. food/fuel/feed/timber/fibre)

Conversion from reduced to no tillage decreased crop yields abruptly from the beginning of the experiment. In this regard, N fertilization and occasional tillage could improve crop productivity in no tillage woody cropping systems.

7.5 Other conflicts

There is a lag between the observed improvements in some soil physico-chemical properties and those in crop yields when reduced tillage is adopted, which hamper farmer adoption because the benefits are not immediate.

8. Recommendations before implementing the practice

Selection of the appropriate cover crops species and right mixture between legume and non- legume and flexibility in the timing of cover crop mowing according to the climatic conditions.

9. Potential barriers for adoption

Table 87. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Harsh pedo-climatic conditions (semiarid soils with low availability of organic matter, water and nutrients)
Cultural	Yes	Farmer perception regarding the traditional belief that a "clean" and "tidy" orchard must always be free of vegetation except for the trees (Ramos *et al.*, 2010).
Social	Yes	Peer pressure; degree of autonomy in choosing and implementing results; and community support (Borgström *et al.*, 2016; Runhaar et al., 2017).
Economic	Yes	Cost/benefit ratio; benefits of applying green manure under semiarid conditions are not immediate; lack of availability of business models (Ferwerda, 2015).
Institutional	Yes	Lack of economic incentives and support from governments, including subsidies (Runhaar *et al.*, 2017).
Legal (Right to soil)	Yes	Lack of strictness of legislation and standards (Ahnström *et al.*, 2009).
Knowledge	Yes	Lack of: i) awareness among farmers, ii) community feeling, iii) innovativeness, and iv) understanding of the agroecosystem (Ferwerda 2015; Schoonhoven and Runhaar, 2018).
Other	Yes	Lack of motivation.

Photos

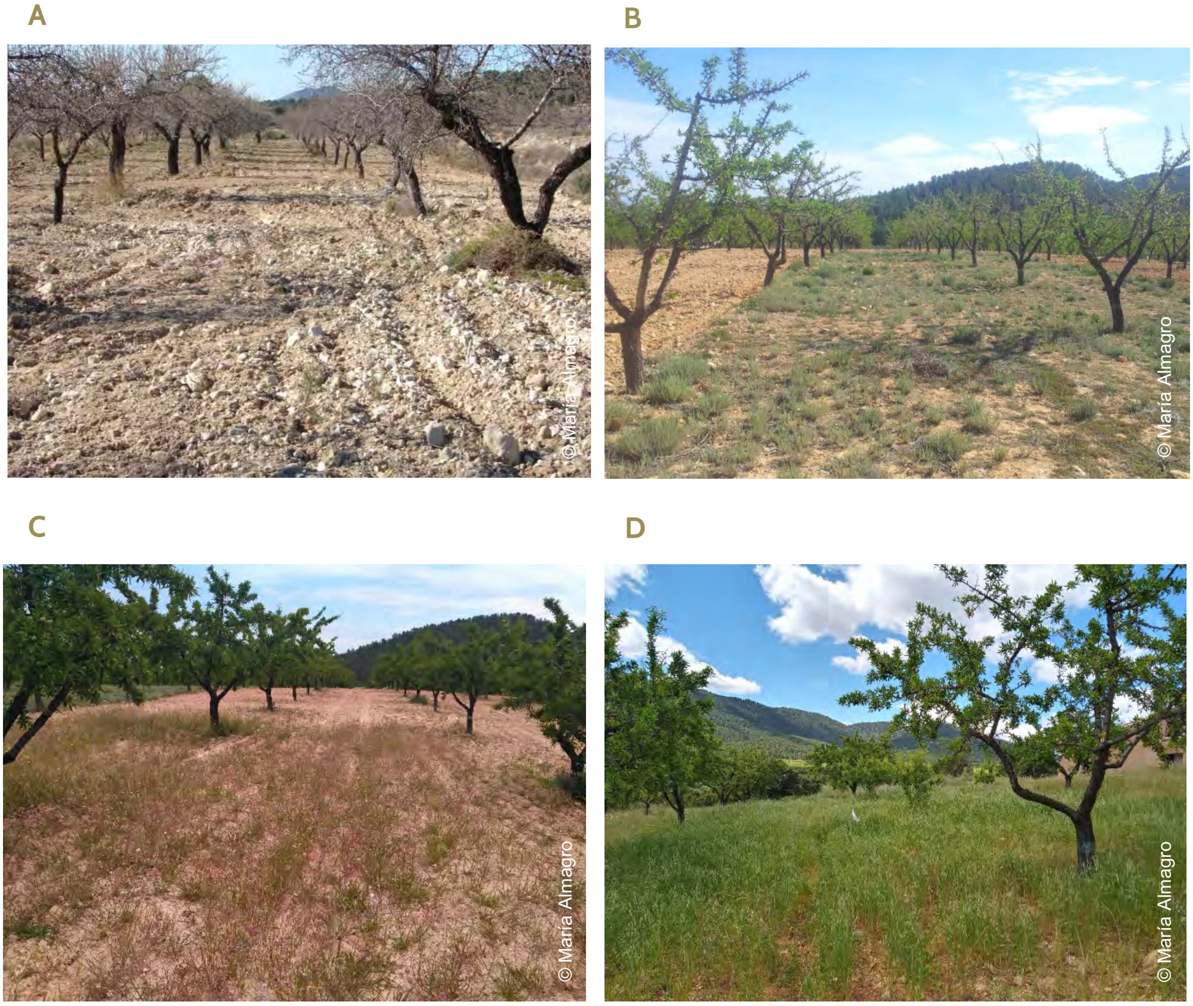

Photo 40. Partial views of the different improved soil management practices showing the aspect of the ground covers

Under no-tillage (B), reduced tillage (C) and reduced tillage with green manure (D) in the rows at the end of the growing season compared to the bare soils in the rows under a conventional (intensive) tillage system (A).

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22. Biochar and compost application in an olive orchard, Spain

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1. Related practices and hot-spot

Biochar, compost applications, organic agriculture; Drylands

2. Description of the case study

A field trial was set up in an organically managed olive orchard in order to evaluate the potential of three fertilization practices as strategies for soil C sequestration. The effects of biochar, compost and their mixture on crop yield, nutritional status of olive trees and the levels of soil organic C were assessed. Trade-offs between C sequestration and N_2O emissions were also evaluated, as well as other soil microbial and biochemical parameters.

Compost was prepared on-site by windrow turning, mixing two-phase olive mill-waste with sheep manure and olive tree pruning at a volume proportion of 50, 25 and 25 percent, respectively (López-Cano *et al.*, 2016). Biochar was made from oak wood by slow pyrolysis at 650 °C, at atmospheric pressure, with a residence time of 15 hours. It had a 67 percent of organic C and a high degree of aromatic condensation (H/Corg molar ratio = 0.32).

The experimental design consisted of four treatments: (i) control (no amendment), (ii) compost, (iii) a mixture of compost/biochar at a 90:10 ratio (dw/dw) and (iv) biochar. Three replicates per treatment were set up, where each treatment included six trees of two adjacent tree rows. Amendments were applied at 20 t/ha at 1 m width at each side of the tree along the irrigation pipelines, following the common practices of the area. This is equivalent to 16 kg/tree or 6 t/ha considering the whole plot area. Amendments were manually applied in May 2013, May 2015 and May 2017 and immediately incorporated into the soil by tractor ploughing at 15 cm depth (Photo 41). No C or N was added to control plots whereas compost, mixture and biochar treated plots received 141, 132 and 50 kgN/ha and 2.15, 2.34 and 4.04 tC/ha at each amendment event.

Soil total organic carbon (TOC), dissolved organic carbon (DOC), water soluble nitrogen (WSN), mineral N (NH_4^+ and NO_3^-) and denitrifying enzyme activity (DEA) were monitored for four consecutive years. During the two years after amendment, CO_2 and N_2O emissions were measured. The number of ammonia monooxygenase (*amoA*) genes copies were also registered after 15 months. More details of the amendments used, the experimental set up and results from the first two years of the experiment are available in Sánchez-García *et al.* (2016).

3. Context of the case study

The field experiment was stablished in the Region of Murcia, located in the Southeast of Spain (coordinates: 38°23' N; 1°22' W). This area belongs to a warm temperate dry climate zone (IPCC, 2006). The mean daily maximum temperature is 20.7 °C and the mean minimum temperature is 11.5 °C. The annual rainfall is 250 mm, which mainly falls in autumn and spring. During the summer, the dry period coincides with the highest insolation rates and temperatures, which is characteristic of the Mediterranean climate. The soil is a Haplic Calcisol (WRB classification), with 57 percent sand and 16 percent clay, 30 percent carbonate and a pH of 8.01. It is subjected to intense soil C mineralization, low organic matter content and intense but infrequent precipitations, which increases the risk of erosion and C losses.

The trial plots were set up in May 2013 in an olive orchard organically managed (Photo 42). The olive trees were 20 years old in a framework of 4 x 7 m^2 and fertilisation consisted exclusively of compost application every two years. Other culture practices consisted of low tillage intensity (three times per year) and deficit drip irrigation during summer periods.

4. Possibility of scaling up

Biochar utilization as soil amendment has been identified as a C sequestration strategy due to biochar high degree of C recalcitrance and aromaticity (UNEP, 2017). Many authors found biochar soil amendment could be used as a strategy to enhance soil fertility while reducing GHG emissions *(Cayuela et al., 2014; Laird, 2008; Verhoeven et al.*, 2017). However, soil responses to biochar amendment are dependent on the biochar characteristics (i.e. feedstock, pyrolysis conditions) as well as on the site properties (climate and soil characteristics) (Jeffery *et al.*, 2015). Biochar feedstocks from local crop residues are of special interest as they may close the loop between local waste disposal and crop production (Sánchez-García *et al.* 2019), thus enabling a step forward circular economy. Biomass carbonization for agricultural use represents a management alternative for vast amounts of agricultural residues, which otherwise are combusted in open fields, causing severe air pollution and increased fire risk (Zhang *et al.*, 2016).

Several areas with similar environmental conditions are currently located in five ecoregions under Mediterranean climate conditions: the Mediterranean Basin, the Pacific coast of North America, southwestern Australia, the Cape region of South Africa, and the central coast of Chile. Olive tree crops are usually cultivated in these areas (Vicente-Vicente *et al.*, 2016). These areas are threatened by a high risk of C losses, where the inputs of organic amendments were identified as a promising strategy to increase SOC (Aguilera *et al.*, 2013).

Additionally, these soils have a large potential for increased SOC stocks as they are far from C saturation (West and Six, 2007) and, given the importance of the expected benefit, the enhancement of SOC stocks of C-poor soils should be considered in priority (Chenu *et al.*, 2019). Moreover, arid and semiarid weather conditions are expected to increase as a consequence of climate change (Collins *et al.*, 2013). Thus, studies developed in arid lands are of high interest as they may be also representative of future scenarios in areas that are expected to suffer increased temperatures and water scarcity.

5. Impact on soil organic carbon stocks

Table 88. Evolution of SOC stocks after 4 years of experiment at the experimental plot in Murcia, Spain

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage potential (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Murcia (Spain)	Warm temperate dry	Haplic calcisol	3.024	Control (no amendment): - 0.068 Compost: 0.035 Mixture: 0.017 Biochar: 0.281	4	15	Increment in SOC storage after 3 amendments (every 2 years) considering the whole plot area	Sánchez-García *et al.*, 2016*

*This reference compiles results from the first two years of the experiment, from 2013 to 2015)

6. Other benefits of the practice

6.1. Improvement of soil properties

Among other soil physical properties, soil water availability is a concern of paramount importance specially in the semiarid and arid regions (Spokas *et al.*, 2012). In a recent meta-analysis, a 9 percent average decrease in bulk density (BD) was registered in biochar amended soils across all textural groups (Razzaghi, Obour and Arthur, 2020). The lower BD facilitates root penetration as well as air and water movement, thus enhancing water availability for plants (Laird, 2008). In this field experiment organic amendments did not result in a significant impact on soil BD, possibly because of the high field heterogeneity.

Previous studies have reported long-term enhancement of nutrient storage and supply as biochar surface oxidation and CEC increases over time (Cooper *et al.*, 2020). In many cases, this is related to the biochar liming effect. Although this biochar property does not have repercussions when soil pH is already alkaline (Sánchez-García, Sánchez-Monedero and Cayuela, 2020) biochar amendment still promotes biological activity and nutrient cycling in calcareous soils (Lejon *et al.*, 2007; Ventura *et al.*, 2014). Compost and mixture amendments resulted in increased dissolved organic carbon (DOC) as well as water soluble nitrogen (WSN). However, biochar amendment alone did not result in increased nutrient availability as the soil nutrient content was poor and woody biochar does not represent a significant nutrient source.

The size of total bacterial population was positively correlated with nitrifying bacteria and denitrifying enzymatic activity (DEA), showing the positive impact of organic amendments on the biological properties of the soil. Moreover, an interesting synergistic effect was observed when compost and biochar amendments were combined, as DEA reached the highest values in mixture-amended plots every year since the experiment was set up (average values in July, the month of maximum activity, were 19.47, 38.95, 76.11 and 10.91 ngN/g/h for control, compost, mixture and biochar amended plots respectively). As there were no differences in soil nutrient content between compost and mixture- amended plots, the increased DEA was a consequence of a higher biological activity in mixture treatments. Nitrifying bacterial population was also larger in mixture-amended plots ($3.78 \times 10^8 \pm 0.33 \times 10^8$ *AmoA* gene copies), an effect that was not observed in compost nor biochar amendments alone ($2.22 \times 10^8 \pm 1.55\ 10^8$ *AmoA* gene copies average value for the rest of treatments).

6.2 Minimization of threats to soil functions

Table 89. Soil threats

Soil threats	
Soil biodiversity loss	Enhanced microbial activity (Sánchez-García *et al.*, 2016).
Soil compaction	Enhanced aggregate stability (Blanco-Canqui, 2017) and reduced bulk density (Blanco-Canqui, 2017; Razzaghi, Obour and Arthur, 2020).
Soil water management	Increased plant available water (Blanco-Canqui, 2017; Razzaghi, Obour and Arthur, 2020).

6.3 On provision services (e.g. food/fuel/feed/timber/fibre)

There were no significant differences in the production of olives between treatments. The high field variability may have offset the possible differences between the treatments. However, olive trees are characterised by their slow responses to fertilisation changes (Fernández-Hernández *et al.*, 2014) so we cannot discard effects on the olive productions to be distinct in a longer term (Table 90).

Table 90. Olive production according to the different treatments in the 2017 campaign

Treatment	2017 campaign (t/ha)
Control	6.96 ± 1.10
Compost	7.75 ± 0.66
Mixture	7.44 ± 1.12
Biochar	8.71 ± 1.40

Values given are average values (n=3) ± standard deviation

6.4 Mitigation of and adaptation to climate change

Biochar treatment led to the highest and more persistent increase in TOC in the topsoil layer (15 cm depth). The N_2O emissions were generally low (between 0.14 and 0.24 kg N_2O-N/ha/yr) and no significant differences between treatments were registered.

6.5 Socio-economic benefits

At present, the use of compost and biochar as organic amendments are limited by the elevated costs of production and application. In the case of biochar, its agricultural use is also limited by the low availability of pyrolysis units. In recent years, the increasing concern about the contribution of burning biomass in the open field to GHG emissions has led to many olive trees producers to grind their pruning residues and apply them directly to the soil. However, this has posed a risk to the spread of soilborne pathogens (Benyei *et al.*, 2018). Both composting and pyrolysis of biomass are techniques that allow the recycling of nutrients in agriculture while they guarantee the sanitization of the biomass. However, the short-term benefits of compost and biochar application in soil do not economically compensate for their costs. This fact could be reversed with the development of policies that offer solutions to the disposal of pruning wastes and promote bio-circular economy and C sequestration.

7. Potential drawbacks to the practice

7.1 Increases in greenhouse gas emissions

GHG emissions under this Mediterranean dry climate were generally low and only the coincidence of soil moisture (after drip irrigation) and high temperatures during the summer caused some N_2O pulses. The N_2O emission factor (%EF, *i.e.* the percentage of fertilizer N applied that is transformed and emitted on-site as N_2O) was very low and similar for all treatments (<0.1 percent). Biochar did not decrease N_2O emissions compared to compost treatment. Furthermore, compost amendment did not increase N_2O emissions despite the higher N and C availability.

7.2 Other conflicts

Physical processes may lead biochar transport off-site.

8. Recommendations before implementing the practice

The terms biochar and compost refer to a wide spectrum of organic amendments and need to be properly characterized prior to their utilisation as beneficial soil amendments.

Biochar is characterised by a very low density. Immediate ploughing into the soil after biochar is applied is recommended to avoid its transport off site (i.e. by wind).

Given the current low availability and high market prices of biochar, implementing on-field pyrolysis systems is necessary to improve the economical balance.

9. Potential barriers for adoption

Table 91. Potential barriers to adoption

Barrier	YES/NO	
Economic	Yes	Low availability and high market prices (Frank *et al.*, 2020).
Knowledge	Yes	Absence of long-term field studies (Jeffery *et al.*, 2015).

Photos

Photo 41. Biochar application by hand onto soil surface and amendment incorporation by tractor ploughing

Photo 42. Landscape image of the field experiment

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23. Syntropic Agriculture in a Mediterranean context

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1. Related practice and hot-spot

Syntropic Agriculture; Dryland

2. Description of the case study

La Loma Viva is a research project for regenerative agriculture that was founded in 2009 on a degraded landscape in Granada, southern Spain. Permaculture was initially used to implement the mainframe design elements of the farm, including renewable energy and water harvesting systems. A collaboration with Ernst Gotsch[5], and his method of Syntropic Agriculture (SA) began in 2016, with the intention to implement a system that would profoundly regenerate the landscape and be agriculturally productive. The objectives of regenerative agriculture are to: improve soil conditions, sequester carbon, enhance the water cycle, increase biodiversity and improve resilience to climate change, whilst also improving the quality of food products. To these ends, SA has been widely and successfully adopted in the tropics but is not well documented in other climate zones. A SA research site was set up at La Loma Viva in 2017 to investigate the potential of this method in a Mediterranean context. It was implemented on an area of 2 150 m^2 (Photo 43) on an existing traditional almond cultivation terrace. In order to create the forest-like system of SA, appropriate plants and trees were chosen, using mainly indigenous species, based on the observation of their functions, to occupy different strata (space) and according to their dynamics of succession (time) (Photo 44, Table 92). The main tree lines were planted 4 metres apart, to grow diverse productive species, maximize photosynthesis, create shade, reduce evaporation and increase biomass production. They were densely stacked with multi-strata tree and plant consortiums, with the aim of achieving 100 percent soil cover with living plants. Interlines were planted with annual and perennial vegetables, hardy indigenous plants and seasonal cover crops. The design, along with management practices such as regular pruning, mimic the form and processes of a diverse natural ecosystem and accelerate natural regeneration within an agroecosystem. SA creates a powerful carbon farming strategy, with multiple social and environmental benefits.

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[5] Swiss geneticist and farmer, creator of the concept of Syntropic agriculture (also see Chapter 6.1.4 of this manual on Syntropic agriculture).

Table 92. List of tree and plant species currently used in the SA system at La Loma Viva

STRATA	STRATA OCCUPATION	SPECIES
Emergent	15 – 20%	Cyprus (*Cupressus sempervirens*), White poplar (*Populis alba*), black poplar (*Populis nigra*), Black locust (*Robinia psuedoacacia*), Stone pine (*Pinus pinea*)
Canopy	40%	Mediterranean hackberry (*Celtis australis*), Carob (*Ceratonia siliqua*), Fig (*Ficus caricus*), Black walnut (*Juglans nigra*), Black mulberry (*Morus nigra*), Olive (*Olea europea*), Avocado (*Persea americana*), Holm oak (*Quercus ilex rotundifolia*), Ash (*Fraxinus angustifolia*), Willow (*Salix alba*)
Medium	60%	Persian silk tree (*Albizia julibrissin*), Almond (*Amygdalus communis/Prunis dulcis*), Strawberry tree (*Arbutus unedo*), Citrus varieties (*Citrus sinensis*), Turpentine tree (*Pistacia terebinthus*), Apricot (*Prunus armeniaca*), Plum (*Prunus domestica*), Peach (*Prunus persica*), Pomegranate (*Punica granatum*),
Low	80%	Vetiver (*Chrysopogon Zizanoides*), Cardoon (*Cynara Cardunculus*), Artichoke (*Cynara scolymus*), Prickly pear (*Optunia ficus indica*), Napier grass (*Pennisetum purpureum*), Mastic (*Pistacia lentiscus*), Retama (*Retama sphaerocapa*), Rosemary (*Rosmarinus officianalis*), Creeping rosemary (*Rosmarinus repens*), Santolina (*Santolina rosmarinifolia*)
Ground	15 – 20%	Asparagus (*Asparagus Officinalis*), Sour fig/ice plant (*Carpobrotus edulis*), Fennel (*Foeniculum vulgare*), Sage (*Salvia officinalis*), Santolina/cotton lavender (*Santolina Chameacyparissus*), Esparto (*Stipa Tenacisma*), Thyme (*Thymus*), Strawberry (*Fragaria × ananassa*)

All strata (Annuals)	Can be planted in interlines or spaces in tree lines.	**Annual vegetables** (e.g. corn (*Zea mays*), tomatoes (*Lycopersicon esculentum*) , peppers, lettuce (*Lactuca sativa var. capitata*), sunflowers (*Helianthus annuus*), potatoes (*Solamum tuberosum*), onions (*Allium cepa*), garlic (*Allium sativum*), broccoli (*Brassica oleracea var. botrytis*), kale (*Brassica oleracea var. acephala*), chard, aubergines (*Solanum melongena*), pumpkins (*Cucurbita spp.*), melons (*Cucumis melo*), beetroot, courgette, chickpeas (*Cicer arietinum*)) **Annual herbs** (e.g. basil, coriander, parsley, dill) **Grasses and cover crops** (e.g. Sudan grass, sorghum (*Sorghum bicolor*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), oats (*Avena spp.*), alfalfa (*Medicago sativa*)) These plants make up a large proportion of the `placenta´ stage of succession
Notes	- Species are planted by strata (i.e. vertical layers based on the space they will occupy in relative height and according to their light needs) - Species are planted according to succession (i.e. time / how long they will stay in the system) e.g. placenta (maximum 24 months), secondary (5-80 years), climax (over 100 years) - The percentages of strata occupation represent more than 100 percent cover, to account for overlaps between different strata - Tree species are planted at 1m intervals with other plants in between (dense planting enables farmer to prune and thin out at regular intervals and choose the most healthy and productive individuals, providing maximum photosynthesis and biomass) - Tree lines are 50-80cm wide and 4m apart - Number of initial trees planted per hectare: 2 500 - Interlines planted with annual and perennial vegetables, aromatic and indigenous plants and/or cover crops/grasses	

This chosen to occupy different strata (space) and according to their dynamics of succession (time).

3. Context of the case study

The region is classified as Warm Temperate Dry, Mediterranean South. It has characteristically hot, dry summers and receives an average of 250 mm of rain annually. It has an east, seaward facing, exposed upslope position, which is subjected to strong coastal winds and had a long history of agricultural exploitation and tilling. The initial research site for SA, was an existing almond cultivation terrace (Photo 45a), where 2 150 m^2 was set aside and converted to the SA system (Photo 45b). The farm had been left fallow for 3 years before implementation began. Given the minor impact of this short fallow[2] a new approach was needed to achieve better levels of soil organic matter content and general improvement of the area.

The Mediterranean regions globally are under immense threat from desertification, drought and availability of fertile soil suitable for crop production (Zdruli, 2011). The Mediterranean biomes are notable for their high levels of biodiversity and endemism, exceeding the combined floras of tropical Africa and Asia (Arroyo and Cavieres, 1991) yet they are also recognized as some of the most endangered areas (Underwood *et al.*, 2009) and are predicted to experience the greatest threats to biodiversity due to their sensitivity to changes in land use and climate (Sala *et al.*, 2000). The southern Spanish region of Andalusia is particularly vulnerable to climate change, due to increased irregularity of rainfall (resulting in droughts and floods), lack of water availability (due to overexploitation of aquifers), forest fires and soil erosion (Massot, 2016). Along with these global challenges, the surrounding area has experienced massive abandonment of traditional farming on terraced fields and is now dominated by Spain's largest plastic greenhouse cultivation areas. This form of agriculture often results in environmental pollution and loss of natural vegetation, simultaneously requiring heavy inputs of water, chemical fertilizers, herbicides, pesticides and plastics. In this region, if we consider the effects of climate change, the heavy exploitation of natural resources in conventional agriculture and other factors affecting the degradation of ecosystems here, it becomes clear and imperative to research agricultural practices which have a regenerative potential. Global hotspots for SOC sequestration include eroded, degraded and depleted soils (Lal, 2018) - such as those found in this part of the Mediterranean. Based on the positive results we have observed from the current SA study and the numerous benefits which will be outlined below, SA presents a good opportunity for C sequestration, reduction of inputs and resilient food production in more arid landscapes.

4. Possibility of scaling up

SA has been implemented successfully on many agricultural sites in the tropics on a bigger scale (Andrade, 2018). The current study is one of only a small number of pioneering SA implementations outside of the tropics and aims at continued research on the possibilities of both implementation and scaling up in a Mediterranean context.

There are two main factors affecting the scaling up of SA:

1. Knowledge: For SA to be implemented, it requires some understanding of the processes, management and species selection necessary for the system. There is currently not much available literature on SA.
2. Mechanization: The development of machinery adapted for SA would be advantageous.

The role of SA in reconciling environmental regeneration with agricultural production would reach its potential of being scaled up by overcoming these technical, institutional and also economic barriers.

5. Impact on soil organic carbon stocks

Soil samples were taken in 2020 from the SA site (which was part of a traditional almond cultivation terrace system) and on an adjacent almond terrace under business as usual (BAU) practice of annual tillage (corresponding to the baseline C stock) (Photo 46). Samples were taken at 0-20 cm depth. Bulk density was 1.09g/cm3 on the BAU site and 1.01 g/cm3 on the SA site. The additional storage was estimated from the difference in SOC stocks between the two sampled plots. The SA trial shows significant increase of C stock of 14.08 tC/ha (Table 93).

Table 93. Changes in SOC stocks after 3 years of SA implementation compared with an adjacent BAU site on 0-20 cm depth

Location	Soil type	C stock on adjacent plot (BAU) (tC/ha)	C stock at La Loma Viva (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Reference
La Loma Viva, Gualchos, Granada, Spain	Calcisol	31.17	45.25	4.69	3	La Loma Viva (2020)

Ten samples were taken from the BAU site (ploughed almond terrace, neighbouring land) and ten samples were taken from the SA site (converted part of almond terrace, La Loma Viva farm)

Differences in C sequestration between the BAU and sample site were observed after SA implementation. SA promotes carbon sequestration through: **high density planting** (with the benefit of multiple root systems and an increase in micro-organisms), **regular management and pruning** (to stimulate vegetative growth of plants and reduce senescence) and **through increased organic matter** (with the application of 30-40cm of biomass mulch to the SA site over the three years of implementation). Further C sequestration is predicted in following years with SA, as it promotes many ways in which SOC can be increased according to current scientific understanding, i.e. (i) dense stacking of multi-strata, multi-species plant configurations, (ii) facilitating a natural succession of plant species with the aim of incorporating climax species (such as olive and oak) which have a potential lifespan and therefore C sequestering capacity of several hundred years or more (iii) trees, plants and mulch provide protection against erosion and (iv) simulating natures strategy of forest development, with all the beneficial synergisms of such a system, achieving soil carbon yields both above ground and root derived.

6. Other benefits of the practice

6.1. Benefits to soil properties

Physical properties

SOC increases after the implementation of SA in comparison with BAU practice: from 2.46 percent to 3.86 percent (La Loma Viva, 2020). Three years after SA implementation, changes in soil colour are observable (Photo 47). Improved water infiltration and reduced runoff was observed on the SA study site, likely to be due to soil aggregate formation caused by the beneficial effects of multi-species plant consortiums and the permanent supply of exudates through their roots, as well as the presence of micro-organisms and soil fauna breaking down the organic matter. Changes in the volumetric density when compared to the site under conventional practices attest to less soil compaction (Table 94).

Chemical properties

No chemical fertilizers, pesticides or herbicides are used in the system. It appears that pH raised slightly in the SA site (pH measured 8 on the SA site in 2020 compared with 7.72 on the BAU site in 2020), most likely due to the addition of bases in tree litter. Laboratory data point to an increase in magnesium and potassium, as well as available phosphorus and nitrogen when compared to the BAU sample (Table 94). A handful of animal manure (250g) was used for the planting of each tree in the first year and for the planting of the annual vegetables. While this small input of manure and other potential factors (i.e. less erosion in the SA area) may help to explain the increase in phosphorus, organic matter plays one of the most significant roles in phosphorus availability, along with the subsequent action of soil micro-organisms in processing phosphorus into plant available forms. Availability of phosphorus increases with the addition of organic matter (Prasad and Chakraborty, 2019).

Biological properties:

Large quantities of mixed variety, woody and herbaceous biomass have promoted the visible growth of beneficial fungi and a diverse range of soil macro and micro-organisms, along with their beneficial actions in the soil. The density of plants and the thick layer of mulch on the ground creates a synergistic feedback loop whereby the plants feed the micro-organisms and they in turn help to provide nutrients for the plants and trees. SA can assist in restoring areas with low soil fertility by providing organic matter to promote nutrient cycling (Ingham, 2000; Peneireiro, 1999).

Table 94. Comparison of physical and chemical properties between the BAU and the SA site (La Loma, 2020)

	BAU site in 2020	SA site in 2020
Bulk density (g/cm3)	1.09	1.01
Available P (mg/kg)	12.6	91.7
Available N (mg/kg)	2.25	3.11
Mg (meq/100 g)	1.31	3.29
K (meq/100 g)	0.43	0.95

6.2. Benefits to soil properties

Table 95. Soil threats

Soil threats	
Soil erosion	Soil is covered by mulch and dense, diverse living plant material with multi-strata root depths. This has reduced water and wind erosion that was observable in the past. No tillage has reduced erosion.
Nutrient imbalance and cycles	Lab results after 3 years of SA, showed a marked increase in available phosphorous, along with increases in nitrogen, magnesium and potassium. Increased soil organic matter (and the effects of micro-organisms) benefits nutrient cycle and increases humid substances necessary for nutrient storage (due to less evaporation). (Table 94)
Soil salinization and alkalinization	SA improves drainage due to multiple plant roots reducing salinization. Less irrigation is required compared with conventional farming (excessive use of irrigation in dry climates, with high evaporation rates largely responsible for salinization in the Mediterranean).
Soil contamination / pollution	SA does not cause any contamination.
Soil acidification	No chemical fertilizers used, particularly nitrogen (responsible for acidification). The cycling of plant biomass reduces and interrupts soil acidification, illustrated by a slight increase in soil pH on site.

Soil threats	
Soil biodiversity loss	Visible increase in soil biodiversity due to: increased biomass/mulch (creates habitat), diverse plant cover, limiting soil erosion and not using chemical agricultural products. Woody biomass from trees increases fungi and promotes healthy soil life.
Soil compaction	Compaction reduced by not using heavy machinery or tillage and having permanent soil cover by plants and mulch, attested by a reduction in bulk density (Table 94). Designated pathways limit compaction by humans.
Soil water management	SA shows positive impacts on soil hydrological properties: increased water holding capacity from multiple root systems, reduced runoff, erosion and evaporation (Miccolis *et al.*, 2016).

6.3 Increases in production (e.g. food/fuel/feed/timber)

In the current study, an area which was previously designated solely to almond cultivation, is now a diverse, mixed polyculture system producing food, fuel (firewood), timber, fodder (especially for bees) and many other useful products. The almond trees that were existing in the research area appear to exhibit higher yields than before SA implementation and in comparison, with the rest of the trees on the same terrace, which had no SA. In general, almond production on these types of terraces has declined dramatically, mainly due to the severe degradation of soils (Ruecker *et al.*, 1998).

As highlighted by Toensmeier (2016), the impact on yields with agroforestry and SA can be difficult to measure given the complexity of these systems. In the coming years it is estimated that production from the established tree systems will significantly increase overall yields in the SA site. Annual and perennial vegetables can be grown in between the tree lines, which enables an income to be earned while the trees are establishing.

The reduction of inputs, along with their associated costs, is also a beneficial factor for production. Local conventional farmers have high expenses on plastics, chemical fertilisers and biological or chemical pest control, all of which are absent from SA. The additional shade provided by the tree lines and the soil covered by biomass, mitigates irrigation demand by reducing evaporation. In the current study the tree lines were only irrigated during the first 1-2 years, for saplings to establish.

6.4 Mitigation of and adaptation to climate change

SA presents an opportunity for diversified production, advantageous in reducing the risk of single crop failure and fostering a resilient agricultural system in fluctuating climate change. We have shown above that the implementation of SA is able to sequester a significant amount of additional carbon. Increased photosynthesis through densely stacked, stratified plants and trees, plays an important role in reducing atmospheric carbon dioxide (CO2). SA also creates micro-climates (due to the shade and wind protection from trees) to reduce negative weather impacts. Yet probably the most important factor of SA in mitigating climate change is through the reduction of inputs – i.e. limiting fossil fuel consumption of heavy machinery, and not using chemical fertilizers and reducing irrigation. With benefits such as these, agriculture can shift from being part of the climate problem to a significant part of the solution (Toensmeier, 2016). The beauty of these systems is that they are able to reduce threats and assist mitigation in an integrated and synergistic way (Duguma, Minang and van Noordwijk, 2014) much like natural ecosystems.

6.5 Socio-economic benefits

The diversified yields of SA at La Loma Viva provide a wide range of useful and commercial products, including many staple crops for personal consumption, thereby promoting local food security.

Abandoned almond orchards are common in the region as farmers are no longer able to make a living from almond production. The present experience, with the appropriate incentives to promote it, could offer an alternative use of these orchards while recovering their fertility, presenting a potential economic and environmental solution in this area.

An important benefit of SA, particularly relevant to our project (in a hot, dry climate) is that it greatly improves the working conditions and wellbeing of farmers. Workers have less exposure to the damaging effects of sun and heat. In the current study, after 3 years of SA, there was a significant increase in the amount of shade in the area and amelioration of local air temperatures, due to the mitigating effects of trees (Montagnini, 2004). Ambient temperature was measured over several locations on the SA site, showing an average of 5-10 °C less compared with full sun on the BAU site. The serious threats of heat and sun on farm workers are a major concern globally (Staal Wästerlund, 2018). Moreover, SA reduces farm workers exposure to other agricultural hazards such as toxic pesticides.

6.6 Other benefits of the practice

SA has a huge impact on increasing biodiversity, as it mimics complex natural systems. In the current study we have observed an increase in birds and other pollinators, beneficial insects, as well as other wildlife coming into the system. Evidence from international studies have shown a marked increase in the abundance of species in agroforestry systems when compared with neighbouring forests (Bhagwat, 2008) or conventional agriculture (Toensmeier, 2016).

An unique aspect of SA is that it has an aesthetic value by creating beauty (Photo 48). Our experience is that SA provides a space for recreation, inspiration and an opportunity to observe and connect to nature, leading to improved quality of life and wellbeing. Our local workers have also expressed an increased sense of pride and enjoyment in their work, especially when they see the many ecosystem benefits evolving (authors personal communication).

7. Potential drawbacks to the practice

7.1 Conflict with other practice(s)

Although SA can and is being adapted in its implementation to be incorporated with other practices, in essence it represents a paradigm shift in agriculture. A change in mindset and habit is necessary. The adoption of regenerative agriculture also requires a systemic transformation, where farmers can be fairly remunerated both for the provision of products as well as ecosystem services.

7.2 Decreases in production (food/fuel/feed/timber/fibre)

Shifting from conventional monoculture to SA may lower production initially while perennials are establishing (Miccolis *et al.*, 2016). The long-term positive impacts of reduced inputs (such as irrigation, fertilisers, etc.) and increased ecosystem benefits (soil fertility, climate mitigation, etc.) can make up for any initial reduction in yields. While diverse crop production is more resilient and provides many necessary products, it can be difficult to make it economically viable in the current global food system and market (particularly for small scale farmers).

7.3 Other conflicts

The initial implementation of SA can be costly, although inputs and costs decrease exponentially over time. Farmers (who are often financially stressed) usually have no economic incentive to adopt environmentally regenerative practices such as SA.

8. Recommendations before implementing the practice

Knowledge is the foremost recommendation for the successful implementation of SA. Farmers should familiarise themselves with concepts such as stratification and succession, as well as appropriate species selection for their particular climatic conditions. SA is a fairly pioneering method, which at this point requires some experimentation and learning from one’s system.

9. Potential barriers for adoption

Table 96. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	SA can be applied in most conditions (climatic, soil type, topography etc.) according to specific adaptations to the design.
Cultural	Yes	It involves a paradigm shift and change of mindset. Also, a commitment to constant learning (Suvedi, Jeong and Coombs, 2010).
Social	Yes	The change to SA, particularly diversified crops, can complicate the use of certain farm machinery, processing equipment and access to markets.
Economic	Yes	Cost of implementation, short term economic necessity and economic policy are common barriers to adopting sustainable practices like SA.
Institutional	Yes	Institutions that govern economic and educational resources do not adequately incentivise shifting to environmentally regenerative practices.
Knowledge	Yes	At present there are only a handful of scientific and educational resources on SA. Knowledge might not be available for specific farming or climatic situations.
Other	Yes	Scaling up can be difficult because specialized machinery is not available on the market (Andrade, 2019).

Photos

Photo 43. Shows area of SA implementation 2 150m^2 on existing almond terraces (green area on right side of photo) Year 3. Gualchos, Granada, Spain. 28-06-2020

Photo 44. Shows species of plants and trees of different strata and phases of succession. 28-06-2020 Year 3. Gualchos, Granada, Spain

Photo 45. a) The initial research site for SA, an existing terrace, in February 2017 (Year 1); b) Same area in June 2020 (Year 3), Gualchos, Granada, Spain

Photo 46. Location of the BAU site and SA site. The BAU site is in purple and the SA site is in green

Photo 47. Difference in soil colour between baseline (left sample: ploughed terrace) and after 3 years of SA (right sample: SA area) on 28th June 2020. Gualchos, Granada, Spain


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Photo 48. Shows the biodiverse and aesthetically beautiful results of SA. Picture taken in spring, also showing interlines being prepared for chili pepper production. 6th May 2020, Gualchos, Granada, Spain

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24. Pickle melon (*Cucumis Melo*) production in Karapınar, Central Turkey

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1. Related practices and hot-spot

Manure application, Mixed-farming; Drylands

2. Description of the case study

Karapınar is located in Central Turkey and has less than 260 mm annual precipitation. The town was almost to be moved in the early 1960s due to sandstorms caused by overgrazing and excess tillage. Following conservation works initiated in 1962 by the Ministry of Agriculture and Rural Affairs, and which is still ongoing, sand dunes were stabilized, and locals restarted rainfed agriculture (Groneman, 1968; Büyük *et al.,* 2020). And, since the late 1990s using water abstraction from groundwater wells, irrigated agriculture has been widespread in the region which tripled the income of local farmers (Büyük *et al.,* 2016). The excessive use of irrigation decreased ground water from 20 meters to 250 meters over almost 30 years, which most probably triggered formation of more than 50 sinkholes in the region varied from few meters to 40 meters deep (Özdemir, 2015). However, local agricultural knowledge adapted to rainfed conditions is promising for both income and environmental protection. One of these is melon production on sand plains. Farmers prepare sandy soils with animal manure and bury 4 melon seeds in each pit with a diameter of 20 cm x 20 cm at 5 cm deep. Row to row spacing is 2 meters, pit spacing is 1 meter on the row. Following germination, two plants per pit are left. Fields are separately allocated for two stages of melon production. One for pickle melons which is harvested at an average size of 3-5 cm before ripening, and another is for fully matured melon from July to end of August. From 1 hectare a total of 30 tons pickle melon is harvested. The labor is provided by the family members and from locals (mainly women) which provides an additional income for village women. The management has been undertaken with low-energy input without irrigation. At the end of the season farmers let their or local sheep to graze the leftovers from the field for post-harvest grazing. Post-harvest grazing also creates an opportunity for diversifying income of farmers.

3. Context of the case study

The sample site is in 37°41′10.41″N, 33°42′8.60″E at an altitude of 1 044 m ASL with an area of approximately 160 km^2. The site has a xeric soil moisture and mesic soil temperature regime, and classified as Brunic Arenols Tephric according to IUSS Working Group WRB (2015), and as Typic Xeropsamments according to Soil Survey Staff (2014). Average precipitation in Karapınar is 283.9 mm/year, which is far below the national average of 643 mm/year (Büyük *et al.,* 2020). The annual temperature average is 11 °C. Mainly natural grasslands, when irrigated wheat, maize, melon, watermelon, tomatoes, and barley are produced.

4. Possibility of scaling up

The case study although site specific (20 x 20 km) has a potential of being scaled up in an area more than 5 100 km^2 where mainly sandy soils are found in Konya Closed Basin of Central Turkey. Under threat of drought in the Basin, the expansion of rain-fed agriculture is expected to spread in near future given its low energy costs with no irrigation, as well.

5. Impact on soil organic carbon stocks

The oldest research undertaken in study site by Groneman in 1968 pointed out a very low organic matter content. However, he did not provide any figure for organic matter. Akça (2001) measured organic carbon in bare sand dunes and determined 0.058% organic carbon. This value is considered as baseline. The present organic carbon content of the site is 1.2 percent which equals to 19.7 tC/ha. Thus, an annual storage potential is estimated as 0.33 tC/ha/yr in the area which is 0.41 tC/ha/yr for protected grassland (Büyük *et al.*, 2020; Table 97).

Table 97. Evolution of SOC stocks on the study site since 1968

Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Warm Temperate Dry	Brunic Arenols Tephric	9.57	0.33	60	0-15	Precipitation lower than 300 mm and dry spells in May threatens rainfed production	Groneman (1968), Akça (2001), Büyük *et al.* (2011), Büyük *et al.* (2020)

6. Other benefits of the practice

6.1. Improvement of soil properties

In the study area small ruminant husbandry is a traditional livelihood and recent government subsidies for large ruminants caused a large amount of animal manure production. The pickle melon producers only apply composted animal manure for the production. Mechanical tillage is very low as the majority of the sowing, hoeing and harvesting is undertaken by family members or local workers. Thus, incorporating organic matter also provides plant nutrients and may support increased soil biological activity. This may lead to improved soil structure and an increase in plant-available water as aggregation provided by animal manure lead to higher water holding capacity. Roughly the 34 tons of organic matter (converted by multiplying 1.2 percent organic carbon of the site with 1.72 - Soil Survey Laboratory Methods Manual, 1992) in one hectare may store 680 tons of water as organic matter can hold 20 times of its weight in water (Reicosky, 2005).

6.2 Minimization of threats to soil functions

Table 98. Soil threats

Soil threats	
Soil erosion	Rough surface resulted from pit seeding plus plant surface coverage prevent sandy soils from wind erosion; In the region fall and early spring winds are very erosive; and during those periods soil surface should be roughened and covered by plant stubbles or mulch. Soil cover at the driest time of the year prevents wind erosion also organic matter creates better soil aggregation against siltation.
Nutrient imbalance and cycles	Designated manure application to pits increase nutrient balance and cycles.
Soil salinization and alkalinization	Sandy soil texture with excess drainage prevent salinity built-up.
Soil contamination / pollution	Pickle melon producers use matured animal manure free of heavy metals or agro-chemicals. Thus, soil contamination or pollution is not a question in this site
Soil acidification	As the soils are rich in bases acidification is not an issue.
Soil biodiversity loss	Composted animal manure provides food to soil microorganisms and no toxic chemical use provide better living conditions to soil organisms. Moreover, minimum tillage do not disturb living organisms in the field. Thus, soil biodiversity is enhanced via pickle melon production (Photo 50).

Soil threats	
Soil sealing	Increasing income from soils prevents construction of buildings.
Soil compaction	Pickle melon production is mainly labor intense management. Machinery only used once during mixing organic harvest wastes to soil then all management is done by family members or local workers which all prevents soil compaction
Soil water management	Ridge till, seeding pits and manure increase soil moisture holding capacity up to 20 times according to Reicosky (2005).

6.3 Increases in production (e.g. food/fuel/feed/timber)

When sandy soils are cultivated, they are protected from excess grazing and produce 30 tons of pickle melon which is sold ca. 333 €/t. Also, leftover plant residues following harvest is 5 t/ha which was used for feeding farmers' or locals' sheep. Post-harvest grazing has an added value as the areas are adjacent to small-ruminant grasslands.

6.4 Mitigation of and adaptation to climate change

Due to low machinery and agro-chemical use and increased organic carbon along with water holding capacity of soils, pickle melon production provide a model for mitigation and adaptation to climate change in warm temperate dry areas of the world.

6.5 Socio-economic benefits

The excessively grazed soils put into production with pickle melon production. Harvesting pickle melon several times provide 5 times as much income to the producers compared to wheat. One-ton wheat grain is 200 € while a tonne of pickle melon is almost 1 000 € in the research area. Moreover, pickle melon production is labor intensive thus local agriculture workers particularly women have the opportunity to be employed in production which creates income.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Actually, in sandy soils there are not any tradeoffs using manure and roughening (conservation soil tillage for wind erosion). Moreover, leaving harvest wastes on soil somewhat provides a kind of mulching.

Table 99. Soil threats

Soil threats	
Soil salinization and alkalinization	Need to monitor soil salinity. While compost and manure are the best way to amend sandy soil, they contain high levels of salt that can accumulate in the soil and damage growing plants if the salt level builds up too high.
Soil compaction	Could be a problem in sandy soils under given vehicle traffic depth.

7.2 Increases in greenhouse gas emissions

According to estimation of FAO EX-ANTE Tool (EX_ACT) (Bernoux *et al.*, 2010), the net GHG balance in soils of annual crops is as 18 t CO_2eq/ha t/year for the studied site.

7.3 Conflict with other practice(s)

Shifting natural grasslands to cultivation decreases the grazing area for local herders. This may cause conflicts however; melon farmers sell harvest leftovers to herders which is preferred by shepherds as they do not need to travel long distances for grazing.

7.4 Decreases in production (food/fuel/feed/timber/fibre)

Negative impact is not the case here as the cultivated areas are overgrazed and cultivating melon has a positive impact on production.

8. Recommendations before implementing the practice

Instructions for pickle melon cultivation, sowing, hoeing and harvesting times are needed.

9. Potential barriers for adoption

Table 100. Potential barriers to adoption

Barrier	YES/NO	
Cultural	No	Because pickle is one of the favorite foods in Turkey particularly its consumption is quite high in cool seasons.
Social	No	As cultivation is labor intensive family members work in the field and local agricultural workers do not need to travel other places for work. They work in fields close their homes.
Economic	No	Compared to wheat pickle melon income is 5 times higher.
Legal (Right to soil)	Yes	Minimum tillage, light machinery, application animal manure are good practices.
Knowledge	Yes	Pickle melon production needs to be introduced, very local knowledge
Natural resource	Yes	Rainfed no problem, if well water not good in the region.

Photos

Photo 49. Pickle melon field in Karapınar, Central Turkey

Photo 50. Pickle melon field with prairie dog hole

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25. Irrigated wheat-maize-cotton in the Harran Plain, Southeast Turkey

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1. Related practices and hot-spot

Crop rotations, adequate irrigation; Drylands

2. Description of the case study

The Harran plain is located at the upper Mesopotamia regularly affected by high temperatures reaching 40 °C in summer. The soil moisture and temperature regimes of the region are xeric and mesic respectively, but near the Syrian Arab Republic border in the southern part it is close to aridic (Soil Survey Staff, 1999). The irrigation of the prime soils of the plain (150 000 ha started in 1995) tripled local's income due to 2.5 crops a year (namely a wheat (*Triticum aestivum*) -maize (*Zea mays*)-cotton (*Gossypium spp.*) rotation) and occurred within the framework of Southeastern Anatolia Development Project initiated in mid 1980s (Kankal *et al.*, 2016). Almost one quarter of the Turkey's cotton is produced at Harran Plain. The organic matter of the soils increased from an average of 1.2 percent to close to 2 percent following irrigation and application of fertilizers in widely distributed Fluvents, Vertisols, Cambisols and Calcisols (Kapur, Akça and Günal, 2018). The traditional rainfed cropping included wheat, barley (*Hordeum vulgare*) and lentil (*Lens culinaris*). However, although a large part of the plain has experienced an increase in yield, salinity has occurred after excessive irrigation, which was only seen at few depression areas. And, throughout the plain irrigation-induced erosion processes can be seen (splash, sheet and rill) due to either furrow and surface (flooding) irrigation or sprinkler irrigation, which is rather limited with some areas. However, current wheat-maize-cotton rotation has increased soil organic carbon in Harran Plain almost by 1 percent, but the potential is much higher since in some natural grasslands organic matter content is determined as high as 4 percent (42.9 t/ha) in 15-cm deep soils. This figure could be achieved by incorporating legumes, along with shifting to drip irrigation (Yazar, Sezen and Gencel, 2002), in rotation with soybean (*Glycine max*) or vetch (*Vicia sativa*), which both would have a positive effect on soil organic carbon, water use, and income of farmers as Turkey is a soybean importing country. This necessitates a number of activities that would be led by government such as providing training to farmers, subsidies to legume cultivation, and investing in drip irrigation which will save almost 50 percent of water in the plain.

3. Context of the case study

Harran Plain is located in Southeastern Part of Turkey at 37° 9′7.42″N- 39° 6′26.91″E, 36°41′18.99″N-39° 8′6.63″E, 36°42′35.17″N-38°45′22.00″E, and 37° 8′51.04″N- 38°48′48.47″E with an altitude of 497 m in the north and 354 in the south. The soil moisture and temperature regimes of the region are xeric and mesic respectively. Annual precipitation, evaporation and average temperature are is 365 mm, 1 848 mm, and 17.2°C respectively. Field crops are the main productions in the plain with cotton being the major cultivated plant followed by maize and wheat. The study covers 160 000 ha area, and current irrigation efficiency is assumed to be 47% (Sepetçioğlu *et al.* 2018).

4. Possibility of scaling up

In the Southeastern Anatolian Project (Turkish acronym, Güneydoğu Anadolu Projesi – GAP) region, along with Harran Plain (160.000ha) there are 13 plains that are irrigated or will be irrigated soon (Figure 19). In these plains two crop sequences (Cotton–Wheat; Wheat-Cotton; Wheat-Maize) and preferably four crop sequences (Cotton–Wheat-Maize-Legume) can be applicable which all cover 476 000 ha.

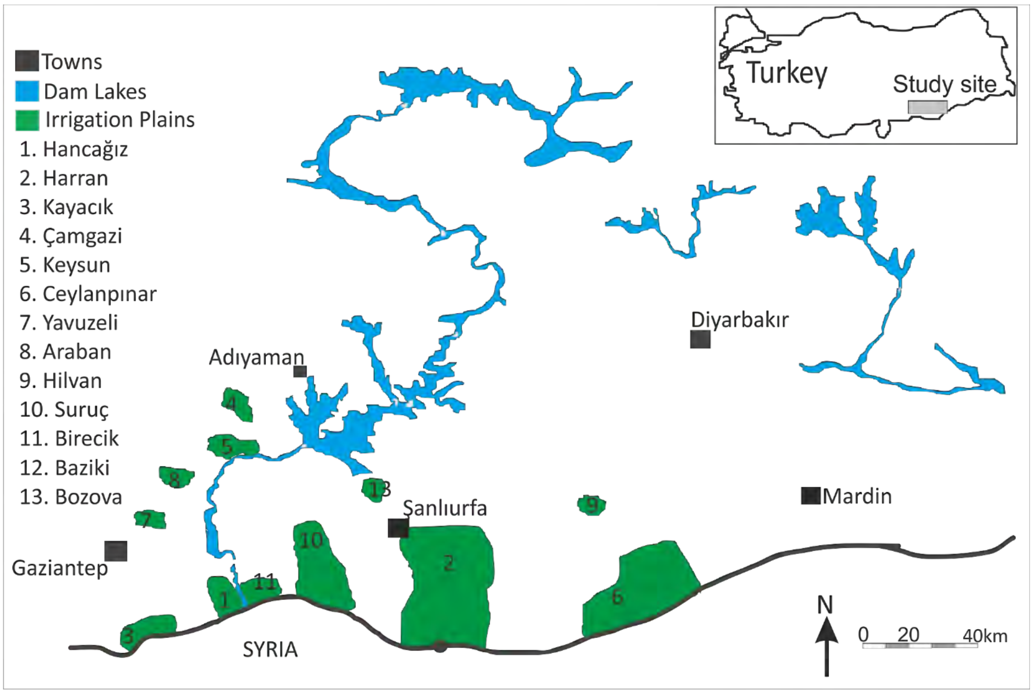

Figure 19. Some of the Southeastern Anatolia Irrigation Project Plains

5. Impact on soil organic carbon stocks

For evaluating C sequestration potential in Harran Plain, the initial reference values were obtained from the soil survey undertaken prior to irrigation in 1988 which had 26 measurement points (Dinç *et al.*, 1988). The recent values are obtained from various studies carried out in the plain which provide soil organic carbon data from more than 400 points (Kaplan, 2016; Bilgili, Küçük and Van Es, 2017; ÇEM, 2018; Table 101)

Table 101. Evolution of soil carbon stocks in 30 years on the studied sites, at 0-10 cm depth

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	Reference
37° 9'7.42''N-39° 6'26.91''E, 36°41'18.99''N-39° 8'6.63''E, 36°42'35.17''N-38°45'22.00''E, 37° 8'51.04''N-38°48'48.47''E	Warm temperate dry	Fluvents, Vertisols, Cambisols, Calcisols	12.2	0.09	30	10	Dinç *et al.* (1988), Bilgili *et al.* (2017), ÇEM, (2018)

6. Other benefits of the practice

6.1. Improvement of soil properties

Vegetation growth in soil as long as 22 months out of 24 months provides good ground cover through the winter months and plant roots enhances microbial activity, nutrient cycling. Roots and increased organic matter improve soil aggregation. Accordingly, physical properties such as water infiltration and aeration are enhanced due to better bulk density. Moreover, continuous cultivation hinders weed growth.

6.2 Minimization of threats to soil functions

Table 102. Soil threats

Soil threats	
Soil erosion	Well-established wheat crop provides good ground cover through the winter months to prevent wind erosion in flat to gentle slopes and rain and runoff erosion processes in moderate, steep slopes unless excess irrigation is applied.
Nutrient imbalance and cycles	Wheat, maize and cotton are effective in utilizing residual soil nitrogen and reducing nitrogen loss by leaching. The post-harvest period of wheat, maize and cotton are ideal for making manure or balanced nutrient applications. The long-term decomposition of wheat, maize and cotton roots and stubble contributes to cycling of nutrients along with enhancing soil carbon.
Soil salinization and alkalinization	Salinity used to be a problem in the depression zones due to water table rise following excessive irrigation, but this problem has been solved with the deep drainage network. However, there is a salinity problem on 2 000 to 3 000 ha due to infrastructure defects.
Soil acidification	Due to high base saturation, low rainfall and high carbonate content acidification is not an issue in Harran Plain.
Soil biodiversity loss	The continuous wheat-maize-cotton-legume cultivation may increase soil biodiversity due organic matter input.
Soil compaction	Farmers every 3 or 4-year subsoil the 30 cm due to hard plough pan developed particularly during harvest due to the high soil clay content.
Soil water management	This rotation along with drip irrigation suits well both for wheat and maize, as root and leaf disease risks are minimized due to adequate moisture, and residual moisture from the cotton or maize may be used by wheat seeds in early November. Also, there 22 Water Union Associations that are willing to cooperate with government and farmers for planning irrigation schedule in the plane.

6.3 Increases in production (e.g. food/fuel/feed/timber)

Harran Plain provides Turkey's 40 percent of cotton, 10 percent wheat and 5 percent of maize production. Thus, the more efficient drip irrigation will significantly increase fiber and food production in the plain without increasing water resource use pressure.

6.4 Mitigation of and adaptation to climate change

Due to high biomass production following harvest locals use cotton residues for cooking and heating purposes which decreases use of fossil fuels (Photo 51) however this will prevent mixing residues to soil which would have increase soil organic carbon content.

6.5 Socio-economic benefits

Prior to Southeastern Anatolian Development Project one-hectare field revenue was 500 US Dollars which is now reached to app. 2 000 US Dollars in 35 years i.e. initiation of irrigation in 1995 (GAP, 2019).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 103. Soil threats

Soil threats	
Soil erosion	Although crop cover prevents wind erosion in the Plain which was high prior to irrigation water, furrow irrigation creates a serious threat. Irrigation-induced erosion is at an alarming rate as State Hydraulic Works determined a daily 650 tons sediment transportation from drainage canals (Bilgili *et al.*, 2014).
Nutrient imbalance and cycles	High phosphorous use causes formation of calcium phosphates that are not available for plants due to soils' high pH.
Soil salinization and alkalinization	Excess irrigation which is frequently experienced in the site may cause secondary salinization in depression zones around Akçakale and Harran town (located at 36°51'54.18''N-39° 4'52.52''E at an altitude of 366 m).

Soil threats	
Soil contamination / pollution	Excess use of agro-chemicals may lead to contamination particularly nitrate pollution which sometimes determined higher than 50 mg/l
Soil biodiversity loss	The continuous wheat-maize-cotton cultivation may hinder soil biodiversity unless legumes are cultivated.
Soil sealing	The expansion of Şanlıurfa city center to the Plain may cause sealing problems if local administrators do not take care to this threat (Photo 51).
Soil compaction	As income of farmers increased, they purchased more powerful field equipment which may cause compaction. Moreover, several irrigations from April to September create saturated profile that can be easily compacted with heavy machinery.
Soil water management	The 1995 irrigation system is gravity model which cause inefficient water management which is below 0.5 (Aydoğdu and Bilgiç, 2016) in the region. Pressured systems (i.e. drip irrigation) should be initiated at the soonest for irrigation efficiency as furrow irrigation consumes (Photo 52) almost 60% more water compared to drip irrigation. Moreover, water user associations have some administrative problems such as low fee collection from farmers.

7.2 Increases in greenhouse gas emissions

According to estimation of FAO-EX-ANTE Tool (Bernoux *et al.*, 2010), the net GHG balance of Annual Crops is as 10 773 t CO_2 eq/ha t/year for the Harran Plain.

7.3 Conflict with other practice(s)

Due to intensive cultivation of wheat-maize-cotton crop pattern legume cultivation along with grasslands are neglected by the farmers. Drip irrigation requires relatively high investment and labor compared to furrow or flooding irrigation.

7.4 Decreases in production (Food/fuel/feed/timber/fibre

Excess irrigation may cause lack of water for some parts of the Plain which keep farmers from second crop production. Moreover, the current crop pattern is not suitable for drought management which is likely to occur soon in Turkey due to climate change (Kitoh, 2019).

7.5 Other conflicts

Since irrigation water does not reach some areas in the south of the plain due to excess water use of farmers of the northern part of the Plain, drainage water is used for irrigation. This water requires pumping with electrical energy consumption, so there is a conflict with farmers and electricity fee collectors. And the drainage water's salt (Bilgili *et al.*, 2013) along with nitrate content may be high.

8. Recommendations before implementing the practice

Legumes should be in the crop rotation. Government may provide subsidies for legume cultivation.

9. Potential barriers for adoption

Table 104. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	Soils and climate along with water sources are favorable for the rotation practice.
Cultural	No	Farmers have the long knowledge of cultivation.
Social	Yes	Insufficient education.
Economic	Yes	Legumes are not preferable because no or low incentives.
Institutional	No	Southeastern Anatolian Project Administration have the facilities and opportunity for supporting training and cultivation.
Legal (Right to soil)	No	The rotation is good for soil quality, if legumes are more cultivated, drip irrigation at field is subsidized by government.
Knowledge	No	Institutions, research agencies and non-governmental organizations have the knowledge of crop rotation and efficient irrigation techniques.
Natural resource	Yes	Over irrigation and evaporation losses.

Photos

Photo 51. Cotton harvest residues used for fuel

Photo 52. Excess irrigation of second crop maize in July

Photo 53. Cotton cultivation with furrow irrigation

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26. Organo-mineral fertilization on a Ukrainian black soil

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1. Related practices and hot-spot

Integrated soil fertility management, mineral fertilization, manure additions; black soils

2. Description of the case study

This field experiment (2012-2016) was conducted on a black soil located in the Forest-Steppe zone of Ukraine. Organo-mineral fertilizers (OMFs) in amorphous and granular form (Photo 54) were tested in broadcasted and band applications. The technology of production of OMFs was based on the regulated aerobic composting of manure with addition of mineral components (N, P, K). The three-replicate trials were set up according to a randomized complete-block design, with plot size of 10 m^2. Total N fertilization on each treatment (manure, OMFs, NPK) was 227 kgN/ha during crop rotation. Mouldboard ploughing was applied in all treatments. Soil samples were taken from the depth of 0–20 cm. Soil organic carbon (SOC) content was determined by Turin (wet combustion) method based on dichromate oxidation.

3. Context of the case study

The research was conducted at the State Enterprise «Experimental Farm Grakivske», on an experimental field of National Scientific Center "Institute for Soil Science and Agrochemistry Research named after O.N. Sokolovsky", Kharkiv oblast, v. Novy Korotich (49°58′12.4″N; 36°01′31.7″E). The region is characterized by a temperate continental climate (Forest-steppe). The mean average temperature is + 6.8-7.0 °C and the average annual precipitation is 465-680 mm, although the year 2016 had more rain (745 mm of annual precipitation). The soil is classified as Chernozem podzolic heavy loamy and formed on loess loam parent material. The land is arable and is under temporary agricultural crops, where the soil coverage during the case-study – crop rotation: corn for silage, winter wheat, and barley.

4. Possibility of scaling up

The practice could be applied in different geographic areas and climatic conditions. OMF production could be adapted to meet different specific needs, including organic production. OMF technological solutions could be used by industrial companies and small farmers.

5. Impact on soil organic carbon stocks

The soil C accumulation rates in the OMF treatments were higher than in the manure and chemical fertilizer treatments. The SOC accumulation was strongly influenced by the form of OMF and method of application (Table 105). The highest SOC increment was found with band application of amorphous OMF, accumulating a surplus of 0.62 tC/ha in the 0-20 cm soil layer during one and a half year of crop rotation.

Table 105. Evolution of SOC stocks after 5 years of experiment

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Reference
Ukraine	Cool Temperate Moist	Chernozem podzolic	66	0.12 (band application of OMF)	5	Skrylnyk and Kutova (2016); Hetmanenko, Skrylnyk and Kutova, (2020)
				0.03 (broadcast application of OMF)		

6. Other benefits of the practice

6.1. Improvement of soil properties

Scientifically based application of organo-mineral fertilizers stimulates biological activity, improves soil structure, increases water retention and preserves soil fertility. OMFs provide essential nutrients (Jakub *et al.*, 2019; Skrylnyk and Kutova, 2016), enhance soil physical and chemical properties (Mujdeci *et al.*, 2017; Yilmaz and Sönmez, 2017) and re-establish microbial populations and activities (Alves *et al.*, 2017; FAO, 2017). Integrated use of organic materials and chemical fertilizers is beneficial in improving available N, P and K in the soil (Skrylnyk and Kutova, 2016). Organic amendments have an increasing positive impact on aggregate stability and organic carbon content in the macro and micro–aggregate scale (Yilmaz and Sönmez, 2017).

6.2 Minimization of threats to soil functions

Table 106. Soil threats

Soil threats	
Soil erosion	Reduced runoff and soil erosion following organic inputs as a result of formation of water-stable macro-aggregates (Koelsch, 2017a).
Ntrient imbalance and cycles	OMFs have a balanced composition for particular crop and soil and thus promote a balanced crop nutrient uptake (Skrylnyk and Kutova, 2016).
Soil salinization and alkalinization	The studied soils have no salinity issues. However, it is known that carbon-rich amendments have a positive effect on physical and chemical properties of saline soils (Lakhdar *et al.*, 2009; Rady, 2012).
Soil contamination / pollution	Humic substances in OMFs can reduce metal solubility by formation of stable metal chelates (Ross and Wiley, 1994).
Soil acidification	Organic fertilizer could alleviate soil acidification (Lin and Lin, 2019). The pH value of the OMF produced from manure was 6,5 – 7 (Skrylnyk and Kutova, 2016).
Soil biodiversity loss	OMFs increase soil organic matter level supporting soil biodiversity (Alves *et al.*, 2018).
Soil compaction	Organic matter addition is an efficient way of reducing the effects of field traffic on soil compaction (Mujdeci *et al.*, 2017).
Soil water management	Increased water infiltration into the soil, possibly leading to greater drought tolerance (Koelsch, 2017b).

6.3 On production

OMFs increase crop productivity. It was found that application of OMFs increased the productivity of crop rotation (corn for silage, winter wheat, barley) by 31 – 42 percent compared to the control where no fertilizer was applied (Skrylnyk and Kutova, 2016). A comparative study of the recommended doses of mineral and various types of organic fertilizers showed that the total positive effect from the use of organic-mineral fertilizers is higher than the sum of the effects from the use of organic and mineral fertilizers separately (Beisenova *et al.*, 2019).

6.4 Mitigation of and adaptation to climate change

Organo-mineral fertilizers hold a potential for carbon sequestration and for the reduction of greenhouse gas emissions (Erhart *et al.*, 2015; Skrylnyk *et al.*, 2018). Detrimental effects of drought stress can be reduced by using OMFs (El-Mageed and Semida, 2015). Application of NPK + organic input compared to NPK only emerged as the best management practices for long-term C sequestration (Das *et al.*, 2019). Application of manure potentially offers the opportunity to limit GHG emissions because their storage – a source of methane emissions– is avoided (Prosser *et al.*, 2008).

6.5 Socio-economic benefits

Adequate manure management brings health and environmental, economic and social benefits (Malomo *et al.*, 2018). A resource-efficient, socially inclusive and low-carbon economy is achieved by tapping into waste as a resource, extending the life cycle of valuable materials and increasing the use of secondary materials (UN Environmental Programme, 2013). The practice promotes a rational use of resources and an environmentally friendly manure management. Expected effects include providing additional places to work, obtaining stable yields and recoupment of cultivation costs.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 107. Soil threats

Soil threats	
Soil erosion	In case of OMFs application during ploughing, the surface runoff and soil erosion could be accelerated (Al-Kaisi, Hanna and Tidman, 2004).
Soil salinization and alkalinization	OMFs should be properly processed and tested to ensure their quality and assess risks of increasing salt content (FAO, 2019; Skrylnyk *et al.*, 2019).
Soil contamination / pollution	OMFs should be tested to ensure they contain safe levels of contaminants (FAO, 2019; Skrylnyk *et al.*, 2019).
Soil acidification	OMFs should be properly processed and tested to ensure their quality (FAO, 2019; Skrylnyk *et al.*, 2019).

Soil threats	
Soil biodiversity loss	OMFs should be properly processed and tested to ensure their quality (FAO, 2019; Skrylnyk *et al.*, 2019).
Soil compaction	In case OMFs application during ploughing, soil compaction can occur due to the tillage system (Figuáres, Rockstrèom and Tortajada, 2003).
Soil water management	In case OMFs application during ploughing, soil moisture could be reduced due to the tillage system (Figuáres *et al.*, 2003).

7.2 Increases in greenhouse gas emissions

No direct measurements were done in this study. However, the current IPCC methodology assumes a default emission factor of 1 percent for non-tropical soils emitted as N_2O per unit (N_2O-N/kg N input). So, nitrous oxide fluxes could reach 316 kg CO_2eq/ha/yr after OMF application, whereas methane emissions after field application of fertilizers were considered to be negligible (Weerden *et al.*, 2014). Considering C sequestration under OMFs (440 kg CO_2/ha/yr), the estimated carbon balance is about 124 kg CO_2/ha/yr.

8. Recommendations before implementing the practice

OMFs should be properly processed and tested to ensure their quality (FAO, 2019; Skrylnyk *et al.*, 2019). The usage of OMFs has to be judicious and in line with the International Code of Conduct for the Sustainable Use and Management of Fertilizers (FAO, 2019).

9. Potential barriers for adoption

Table 108. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	OMFs could be used as fertilizer in any soil conditions (Skrylnyk *et al.*, 2019).
Cultural	Yes	Lack of interest and motivation (Eriksen *et al.*, 2017; Misselbrook, Salazar and Wagner-Riddle 2019; Viaene *et al.*, 2016).
Social	Yes	Adoption takes place in a social context, with farmers discussing their ideas with other farmers (Eriksen *et al.*, 2017; Misselbrook, Salazar and Wagner-Riddle 2019; Viaene *et al.*, 2016).
Economic	Yes	Lack of money for establishment, labor and materials, equipment, and laboratory analyses (Eriksen *et al.*, 2017; Misselbrook, Salazar and Wagner-Riddle 2019; Viaene *et al.*, 2016).
Institutional	No	There are no or few specific environmental regulations in most countries for manure management whereas the social pressure to adequately manage manure is increasing (Misselbrook, Salazar and Wagner-Riddle 2019).
Right to soil	No	OMFs application is not related to right to soil.
Knowledge	Yes	Barriers include access to information and technology (Eriksen *et al.*, 2017).
Natural resource	Yes	Limited resource quantity such as manure and inorganic fertilizer is a potential barrier for adoption of this practice.

Photos

Photo 54. Granulated organo-mineral fertilizers

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27. Interrow organic management to restore soil functionality of vineyards

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1. Related practices

Compost applications, intercropping, cover cropping, organic mulch

2. Description of the case study

Soil functionality in vineyards can be unsatisfactory, as evidenced by reduced vine growth, disease resistance, grape yield and quality, and resilience to climatic variations. The cause of soil malfunctioning can often be related to a degradation process driven by improper land preparation, excessive erosion and/or compaction, loss of soil organic matter and nutrients (Costantini *et al.*, 2018b). In the case study, degraded soils showed lower available water capacity and nitrogen supply, a clear reduction of their capacity to store soil organic carbon (34-35% lower in 0-60 cm soil deep) and an increased potential erosion by water, in comparison with non-degraded soils. The aim of the case study was to verify if endogenous or exogenous organic matter yearly supply in vineyard, by intercropping the vines interrow, could restore soil ecosystem functions, and particularly increase soil organic carbon (SOC) stock.

The results obtained after 2 years of treatments were encouraging:

- Mature farm compost (FC) produced with local cow or sheep manure and pruning (40-50 t/ha/y) improved SOC stocks for about 45 percent,
- Dry mulching (DM) with perennial legumes (e.g. clovers, alfalfa (*Medicago sativa*), ryegrass (*Lolium spp.*), vetch (*Vicia sativa*)) increased SOC stocks of 39 percent,
- Green manure (GM) composed by mixed winter legumes and cereals enhanced SOC stocks of 19%.

FC resulted to be the most rapid and clearly observable treatment able to increase soil nitrogen and organic matter content and to improve grapevine health and vigor. FC also proved to be the best strategy to reduce soil compaction and bulk density, while GM and DM gave the best results in terms of aggregate stability increase (Vignozzi *et al.*, 2018). However, the reduction of erosion risk was lower than using GM and DM. DM tended to increase organic matter and biodiversity more than GM, possibly because of the no tillage (Priori *et al.*, 2018b).

3. Context of the case study

The case study regarded 16 organic vineyards from important viticultural areas, producing renown wines or table grapes. Hence, although the case study was carried out at farm level, could be considered representative of warm Mediterranean (Italy, Slovenia, Turkey and Languedoc in France) and Temperate Oceanic climate regions (Gironde and Narbonne, France). In each vineyard, FC, DM and GM were compared with a control (standard farm management without any addition of amendments or fertilizers), located in the same vineyard and experimental layout. The two French farms, with three studied vineyards each, were in Montagne Saint Emillion, Gironde and Narbonne, Aude in Languedoc; the cultivars were Cabernet Franc and Syrah, respectively. The two Italian farms, with three vineyards each, were situated in Panzano, Chianti Classico wine district, and in San Disdagio, Maremma district, and cultivated with Sangiovese cultivar. The two Slovenian vineyards were near Koper and cultivated with Refosk cultivar. The two Turkish vineyards, cultivated with table grapes, were situated in Ceyhan, Sariveli and Tarsus, Dokuzetkne, respectively.

Mean annual temperature ranged from 9 °C in Slovenia until 20 °C in Turkey. Annual precipitation from 581 mm in Turkey, where vineyards were irrigated, up to 938 in Slovenia. Slope varied between 3 and 25%, stoniness from 0 to 40%. Standard soil management was either tillage or natural grass cover. The detailed vineyard characteristics and managements are reported in D'Avino *et al.* (2018) and Costantini *et al.* (2018a).

4. Possibility of scaling up

The case study is adapted for scaling up, because of the wide geographical distribution and representativeness of the experimental plots of the trial, which was carried out in the same years and with same treatments and experimental layout (randomized blocks with three replications) in commercial farms.

5. Impact on soil organic carbon stocks

The annual additional C storage was calculated as difference with the control and included the undecomposed residues passing the sieving of 2 mm. Table 109 indicates that FC caused a mean raise of C storage of 4.35 tC/ha/yr, characterized by a great increase during the first year and a little not significant decrease in the second year of trial. DM had lower increasing potential than FC (1.8 tC/ha/yr), but regular during the two years of experiment. With the GM treatment instead, the biomass produced by cover crops and the effects on soil carbon stock were very variable from site to site, because of different intercrop soil cover. On average, GM showed a good CS increase during the first year (+4.4 tC/ha), followed by a decrease (-4.2 tC/ha) in the second year.

Table 109. Evolution of SOC stocks at 0-30 cm in the 2-year study led in different vineyards of France, Italy, Slovenia and Turkey

Treatment	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)*	Duration (Years)
Farm compost, annually spread on interrow (FC)	From 11.9 to 49.6	+10.3±2.8	1st
		-1.6±3.1	2nd
Polyannual leguminous plants, annually mowed and leaved on the ground for dry mulching (DM)	From 8.3 to 49.6	+1.4±1.6	1st
		+2.2±2.0	2nd
Winter leguminous and cereals, annually incorporated into the soil as green manure (GM)	From 15 to 49.6	+4.4±1.8	1st
		-4.2±1.7	2nd

Source: Detailed information in Priori et al. (2018a)

Climate was spread over warm temperate moist and warm temperate dry locations. Soil types included in the study were Calcisols, Cambisols, Vertisols, and Luvisols

*± standard error of the means (n=20)

6. Other benefits of the practice

6.1. Improvement of soil properties

The tested organic treatments are aimed to restore soil fertility in degraded soils by improving soil organic matter content and biological activity and, through them, all related soil physical and chemical properties. Main improvements are expected for aggregate stability, available water capacity, water infiltration and permeability, air capacity, enzymatic activity, meso and micro biodiversity, and reduction of parasitic nematodes (Landi *et al.*, 2018; Blanco-Pérez *et al.*, 2020).

6.2 Minimization of threats to soil functions

Table 110. Soil threats

Soil threats	
Soil erosion	Decrease of soil erosion (De Baets *et al.*, 2011).
Nutrient imbalance and cycles	Improvement of C and N cycles (Novara *et al.*, 2020).
Soil biodiversity loss	Enhancement of arthropod diversity (Eckert *et al.*, 2020) and collembola abundance (Simoni *et al.*, 2018).
Soil compaction	Decreasing soil compaction (Konopiński *et al.*, 2020).
Soil water management	Increasing soil water storage (Basche *et al.*, 2016).

6.3 Increases in production (e.g. food/fuel/feed/timber)

During the two years monitoring, there were no significant differences on vegetative growth, yield and grape quality among the soil management strategies in degraded areas (Tardaguila *et al.*, 2018).

6.4 Mitigation of and adaptation to climate change

Introducing cover crops in rotations may be a good strategy to decrease N_2O losses (Sanz-Cobena *et al.*, 2014). Increase in SOC stocks can offset greenhouse emissions (Paustian *et al.*, 2016).

6.5 Socio-economic benefits

The adoption of the suggested organic treatments has manifold socio-economic benefit, related to the improvement of the soil ecosystem services. However, the raise of yields and economic profitability is expected to occur only some years after their implementation.

6.6 Other benefits of the practice

The production of compost of good quality is a rather skilled procedure, which calls for a certain farm specialization, which might be difficult to create. A solution may be based upon the setting of a collaborative production of compost involving several local farms. The mechanism foresees that different farms delivery the raw materials to a unique farm, which is responsible for the production of the bulk of compost. Then the compost, suitably matured, is distributed among the conferring farms in proportion to the conferred amount and their needs. This procedure would also be beneficial to increase trust (about the quality of the conferred material on one side, and about the quality of the compost, on the other side) and collaboration between farmers, and it is favored by the presence of already operating local associations of farmers.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 111. Soil threats

Soil threats	
Nutrient imbalance and cycles	Cover crops can compete for nutrients with cash crops (Kaspar and Singer, 2011).
Soil water management	Cover crops can compete with main crops for water, especially in dry climates and in drought years (Blanco-Canqui *et al.*, 2015).

7.2 Increases in greenhouse gas emissions

There are studies that demonstrate how cover crops significantly decrease N leaching without significant effects on direct N_2O emissions (Abdalla *et al.*, 2019). In addition, legumes as cover crops also decrease N fertilizer use and so N_2O emissions. On average, cover crops could mitigate the net greenhouse gas balance by 2.06 ± 2.10 Mg CO_2eq/ha/yr (Abdalla *et al.*, 2019). Although organic amendments can have a negative impact on GHG emissions from soil, there are practices that allows to reduce the risk (Thangarajan *et al.*, 2013). Moreover, it is possible to convert the positive change of SOC stock in potential CO_2 emission reduction by the ratio of CO_2 and carbon molecular weights (IPCC 2006).

7.3 Conflict with other practice(s)

The high production of biomass can affect the passage of machinery in vineyard, so normally these practices are carried out in alternate rows, reversing them the following year.

7.4 Decreases in production (Food/fuel/feed/timber/fibre

Cover crop cultivation in degraded soils can be difficult because of very low fertility, high calcium carbonate content, and/or high stoniness, and may compete for nutrients with grapevine. Cover crops might compete with grapevine for water during exceptional dry winters and springs, or in particularly dry regions. In these cases, it is better to anticipate the mowing and green manuring to early springtime (Priori *et al.*, 2018b).

7.5 Other conflicts

When soil degradation involves deep horizons (> 50-60 cm), the proposed organic treatments cannot solve the problem (at least in the short or medium term). In these cases, additional organic strategies, such as cultivation of deeper soil horizons and/or supplemental additions of organic materials, or the use of deep-rooted cover crops, shall be introduced and tested.

8. Recommendations before implementing the practice

Users should anticipate DM mowing or GM incorporation in dry seasons to avoid water competition and avoid FC spreading before heavy rains to prevent loss for erosion. The nature of degraded soils requires optimum seedbed preparation to grow GM crops. In small highly degraded areas, cover crop seeds shall be mixed with manure or compost, soil, and water, and then carefully sown to increase germination (Priori *et al.*, 2018b).

9. Potential barriers for adoption

Table 112. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	The perception of the environmental benefits produced by the adopted practiced can be low in poorly educated farmers (Fantappiè *et al.*, 2020).
Social	Yes	The economic size of farms can restrain the propension of farmers to innovation (Fantappiè *et al.*, 2020).
Economic	Yes	The time needed to get an economic benefit may discourage farmers (Fantappiè *et al.*, 2020). Potential risk of water competition with vine in particularly dry seasons for GM and DM. FC purchase and transport costs, if not self-produced.

Photos


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Photo 55. Farm compost (manure + pruning residue and/or straw)

Annually spread on interrow (FC) (top); polyannual leguminous plants, annually mowed and left on the ground for dry mulching (DM) (center); winter leguminous and cereals, annually incorporated into the soil as green manure (GM) (bottom)

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28. Cover crops, organic amendments and combined management practices in Mediterranean woody crops

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1. Related practices

Cover cropping, organic mulch, compost applications, manure applications, sewage sludge applications

2. Description of the case study

The aim of the study was to estimate the carbon sequestration rate in soils of woody crops under Mediterranean conditions by comparing the conventional management with the sustainable management. A meta-analysis including 51 references and 144 comparisons was carried out. The conventional management is usually involves frequent tillage, or reduced tillage combined with the application of pre- and post-emergence herbicides. The sustainable management can be either allowing the growth of a plant cover (natural or seeded), applying an organic amendment (e.g. compost, manure, crop residues, sewage sludge) or a combination of both (plant cover and organic amendment). The study considers three different typical Mediterranean woody crops: olive orchards, vineyards and almond orchards. It also takes into account the duration of the study and the different Mediterranean sub-climates (Vicente-Vicente *et al.*, 2016). Of the 51 references included in the meta-analysis only one combined field measurements with modelling, whereas the other 50 references carried out field studies.

3. Context of the case study

The study covers a total of 51 studies assessing woody crops under Mediterranean conditions in nine countries: Spain (33), Italy (7), Greece (2), France (2), Portugal (2), South Africa (2), the Syrian Arab Republic (1), Turkey (1) and California (United States of America) (1). Different Mediterranean sub-climates were considered according to Köppen-Geiger classification (Kottek *et al.*, 2006).

4. Possibility of scaling up

Since the study is a meta-analysis, the results are already scaled-up, can be extrapolated and applied to the three woody crops (olive groves, almond orchards and vineyards) or other woody crops under similar managements in Mediterranean areas.

5. Impact on soil organic carbon stocks

Table 113 shows that the amount of sequestered SOC is directly related to the amount of the organic input and, thus, the highest sequestration rates (5.36 tC/ha/yr) belonged to the studies assessing high organic input rates. However, the authors remark that a combination of allowing the growth of a plant-cover at least in the inter-row area combined with an internal (e.g., pruning debris) or external (e.g., compost) organic input would be the most suitable solution in terms not only of SOC increase (0.72-1.23 tC/ha/yr) but also in terms of nutrient cycling and preserving soils. Importantly, the authors remarked that the SOC increase is slowed down over time and, thus, the highest sequestration rates occurred during the first years after the shift to the sustainable management (1.22 and 0.72 tC/ha/yr for the first five years and for ten years, respectively). In terms of climate influence, the results of the meta-analysis suggest that the aridity would affect negatively the amount of sequestered SOC (0.46 tC/ha/yr), probably due to the lower biomass production because of the lower precipitations. Finally, the authors did not considered irrigation as a driver, since it usually takes place in a small concentrated area (normally near the trunk) and the measurements assessed in the meta-analysis were carried out only in the inter-row area and, thus, excluded the canopy area.

Table 113. Amount of sequestered carbon in the different management in Mediterranean woody crop systems

Location	Climate zone	Number of comparisons	Additional C storage (tC/ha/yr)	Duration (Years)	Management
Mediterranean olive	Warm Temperate Dry and Moist	18	1.10	< 30	CC, mainly spontaneous cover
Mediterranean olive	Warm Temperate Dry and Moist	25	5.36	< 30	OA, mainly high application rate of OMW and PD
Mediterranean olive	Warm Temperate Dry and Moist	22	3.33	< 30	Combined (CC + OA) mainly spontaneous cover, OMW and PD
Mediterranean vineyards	Warm Temperate Dry and Moist	33	0.78	< 30	CC, spontaneous and seeded cover
Mediterranean vineyards	Warm Temperate Dry and Moist	8	0.65	< 30	OA, low application rate
Mediterranean vineyards	Warm Temperate Dry and Moist	4	0.34	< 30	Combined (CC + OA)
Mediterranean olive, almond and vineyards	Warm Temperate Dry and Moist	29	1.22	0-5 (5)	CC
		22	0.72	6–10 (4)	
Mediterranean olive, almond and vineyards	Warm-temperate	43	1.23	< 30	CC
Mediterranean olive, almond and vineyards	Arid sub-climates	19	0.46	< 30	CC

Source: Adapted from Vicente-Vicente et al. (2016)

CC cover crops, OA organic amendments, OMW olive mill waste, PD pruning debris, C stocks averaging 0.88 percent (± 0.41), soils averaging 39 percent sand (± 20 percent) and 26 percent clay (± 13 percent), average depth 34 cm (± 32), average duration 7.7 years (± 6.0)

6. Other benefits of the practice

6.1. Improvement of soil properties

The application of olive mill waste in olive orchards in Southern Spain improved soil physical parameters (aggregate stability and water holding capacity), soil organic N, especially after long-term applications and soil microbial activity (i.e. soil enzyme activities) (Garcia-Ruiz *et al.*, 2012). Similar results were found under spontaneous plant cover (e.g. Aranda *et al.*, 2011 in olive orchards, Almagro *et al.*, 2016 in almond orchards, and Peregrina *et al.*, 2012 in vineyards).

6.2 Minimization of threats to soil functions

Table 114. Soil threats

Soil threats	
Soil erosion	Reduced soil erosion (Gómez *et al.*, 2011).
Nutrient imbalance and cycles	See section 6.1.
Soil biodiversity loss	Preserve soil microfauna (e.g. Nematodes) (Sánchez-Moreno *et al.*, 2015).
Soil sealing and compaction	Increased aggregate stability (Guzmán *et al.*, 2019) and soil structure (Palese *et al.*, 2014).
Soil water management	Increased water holding capacity and soil moisture (Aranda *et al.*, 2011; Almagro *et al.*, 2016; Peregrina *et al.*, 2012; Palese *et al.*, 2014).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Avoiding soil losses in sloping areas and making the agroecosystem more resilient and sustainable might lead to more stable yields in the future. However, only few studies assessed yields under different management systems, and some studies showed no differences between conventional and cover-crop managements in medium-slope areas (Soriano *et al.*, 2014; Palese *et al.*, 2014; Sastre *et al.*, 2016).

6.4 Mitigation of and adaptation to climate change

The increase in the SOC content leads not only to a CO_2 sequestration, but also to an improvement in the soil fertility properties due to the key role that the organic carbon plays into the soil (i.e. improvement in the soil physical, chemical and biological properties) (see section 6.2).

On the other hand, increasing the diversity of plant species (e.g. through the plantation of an inter-row plant cover) increases the diversity of insects and microorganisms, thus increasing the self-regulation and resilience of the agroecosystem. Therefore, after implementing sustainable practices in Mediterranean woody crops the system would be more resistant to diseases or less prone to be affected by extreme climate events, leading to more stable yields (Montanaro *et al.*, 2018; (Michalopoulos *et al.*, 2020).

6.5 Socio-economic benefits

Combined management practices would increase the nutrient inputs to the soil, and reduce the need for inorganic fertilizers and the associated costs. On the other hand, the growth of a plant cover also increases the quality of the landscape, fostering agritourism and other similar activities.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 115. Soil threats

Soil threats	
Soil contamination / pollution	Nitrate, ammonium and heavy metals when applying e.g. sewage sludge, compost (Łuczkiewicz and Quant, 2007).
Soil acidification	pH decrease when applying compost (García-Ruiz *et al.*, 2012).
Soil compaction	With intensive grazing to control the plant cover (Byrnes *et al.*, 2018).

7.2 Increases in greenhouse gas emissions

N_2O emissions can be expected after the application of organic amendments, but the amount is not known. Some IPCC default values could be applied (Tier 1) for their estimation. However, in the meta-analysis the N_2O emissions were not assessed, since they take place not only in the sustainable but also in the conventional management due to the application of inorganic fertilizers and they could even be higher than those from the organic fertilization (Pareja-Sánchez *et al.*, 2020). Regarding the CH_4 emissions, the sustainable management might lead to a net uptake (Sanz-Cobena *et al.*, 2014)

7.3 Decreases in production (Food/fuel/feed/timber/fibre

A decrease in yields in the short-term in highly productive areas (i.e. flat and high fertile soils) is expected when allowing the growth of a plant cover. However, this would depend on the crop, the specific soil conditions (Ferreira *et al.*, 2013) and the specific time when the plant cover is mowed.

8. Recommendations before implementing the practice

In the case of allowing the plant cover in the inter-row area it is crucial that the farmers control it (i.e. mowing, minimum tillage) in spring before the plants start to compete for water with the woody crops (it is usually between late March and early April, depending on the country and the amount and type of biomass covering the inter-row area). In the case of the application of pruning debris, the positive effects on SOC sequestration and soil fertility are higher when the size of the debris are smaller. Therefore, shredding is highly recommendable (Repullo *et al.*, 2012).

9. Potential barriers for adoption

Barriers are mainly **socio-economic** and **institutional**. They arise from the lack of economic incentives for implementing sustainable farming. Since the majority of the studies included in the assessment come from countries within the European Union, it is worthy to mention the lack of a real environmentally-friendly Common Agricultural Policy (CAP), whose main payments so far have been directly related to the crop surface instead of the specific agricultural management practices (Pe'er *et al.*, 2020). The need for specific incentives is based on the resulting more complex agroecosystem after implementing the proposed sustainable practices (Merot and Wery, 2017). More complex agroecosystems imply not only more sustainable systems, but also more difficult and costly managements and, therefore, farmers are less willing to adopt these sustainable management practices if they are not incentivized.

Table 116. Possible barriers

Barrier	YES/NO	
Social	Yes	Increase in the complexity of the system (Merot and Wery, 2017).
Economic	Yes	Increase in the complexity of the system (Merot and Wery, 2017) and lack of economic incentives (Pe'er *et al.*, 2017).
Institutional	Yes	Lack of environmentally-friendly agricultural policies (Pe'er *et al.*, 2017).

Photos

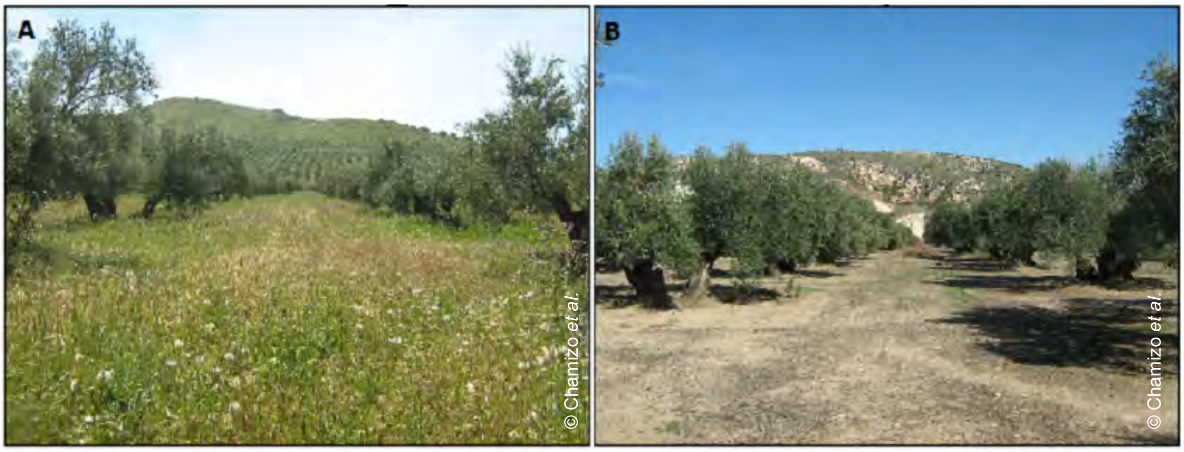

Photo 56. Olive orchard with (A) and without (B) spontaneous plant cover in the province of Jaén, Southern Spain

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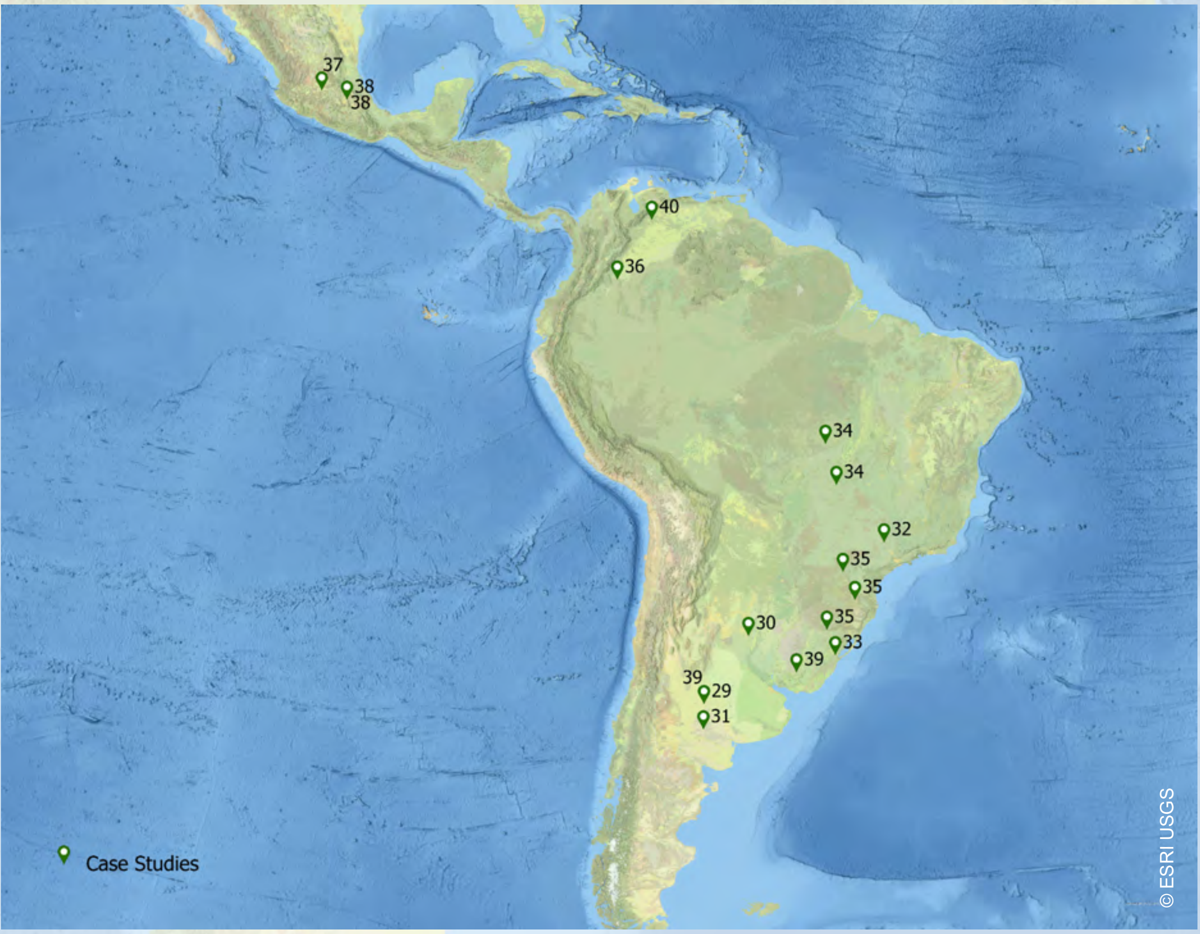

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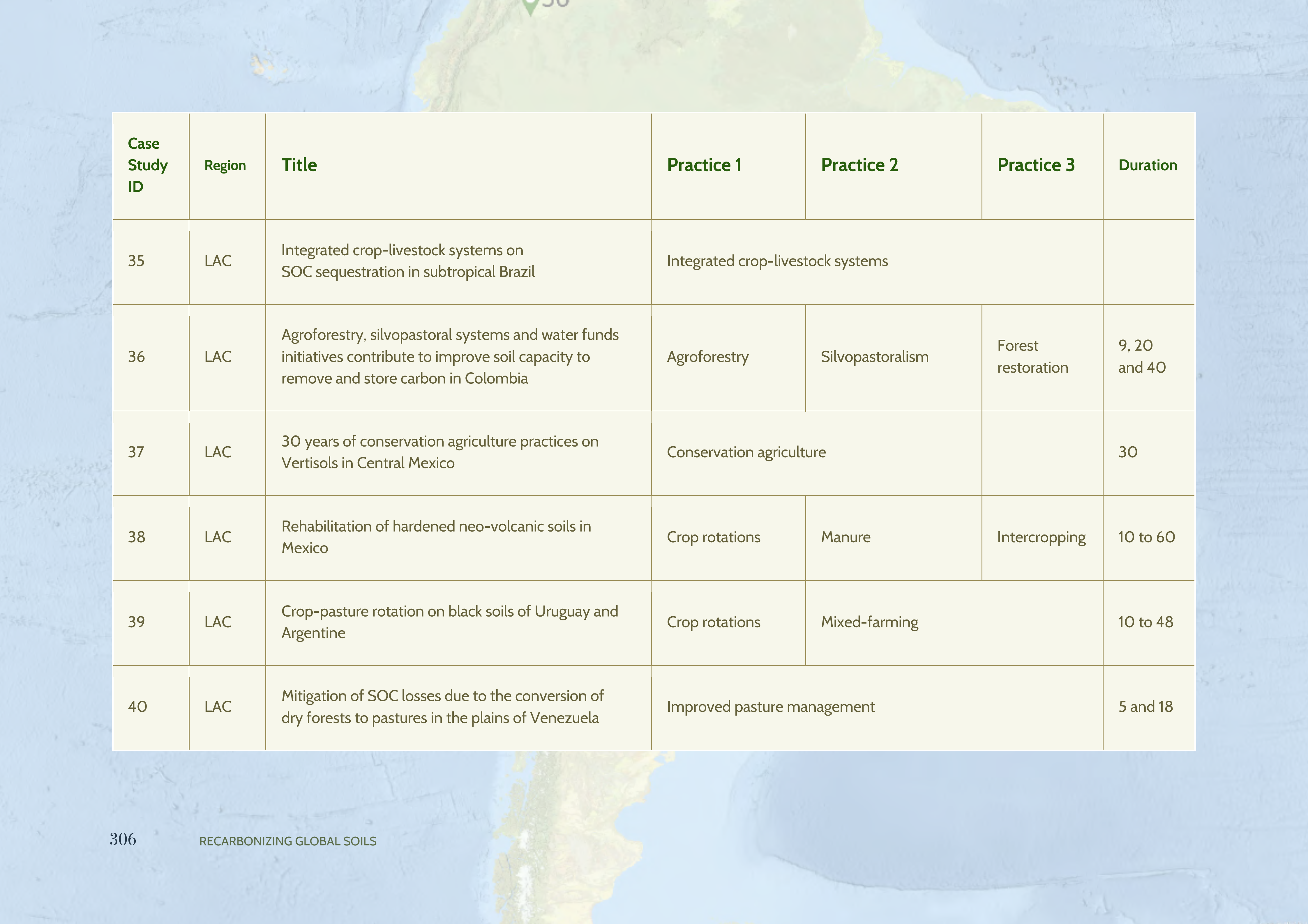
Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
29	LAC	Increasing carbon inputs in agricultural lands in Argentina: fertilizer use, inclusion of cover crops and integration of perennial pastures in crop rotations	Mixed systems	Cover crops	Fertilization	3 to 23
30	LAC	Application of swine and cattle manure through injection and broadcast systems in a black soil of the Pampas, Argentina	Manure			
31	LAC	No tillage and cover crops in the Pampas, Argentina	No-till	Cover crops		4 to 8
32	LAC	Increasing yield and carbon sequestration in a signalgrass pasture by liming and fertilization in São Carlos São Paulo, Brazil)	Liming	No-till		27
33	LAC	Conservation agriculture in lowlands – an experience from South America	Conservation agriculture			
34	LAC	Integrated farming in tropical agroecosystems of Brazil	Sylvopastoralism	Agrosilvopastoralism	Degraded pasture	4 to 12



Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
35	LAC	Integrated crop-livestock systems on SOC sequestration in subtropical Brazil	Integrated crop-livestock systems			
36	LAC	Agroforestry, silvopastoral systems and water funds initiatives contribute to improve soil capacity to remove and store carbon in Colombia	Agroforestry	Silvopastoralism	Forest restoration	9, 20 and 40
37	LAC	30 years of conservation agriculture practices on Vertisols in Central Mexico	Conservation agriculture			30
38	LAC	Rehabilitation of hardened neo-volcanic soils in Mexico	Crop rotations	Manure	Intercropping	10 to 60
39	LAC	Crop-pasture rotation on black soils of Uruguay and Argentine	Crop rotations	Mixed-farming		10 to 48
40	LAC	Mitigation of SOC losses due to the conversion of dry forests to pastures in the plains of Venezuela	Improved pasture management			5 and 18

29. Increasing carbon inputs in agricultural lands in Argentina: fertilizer use, inclusion of cover crops and integration of perennial pastures in crop rotations

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1. Related practices

Mineral fertilization, Cover cropping, Integrated crop-livestock systems

2. Description of the case study

The aim of the study was to estimate soil organic carbon sequestration rates of different agricultural practices oriented to increase carbon inputs to soils, by comparing the “conventional” management against a “sustainable” management. The conventional management generally consisted of continuous agriculture under no-till management, with crop rotations with low residue returns to soils, and limited or no fertilizer use (negative nutrient balances). The sustainable management consisted in practices that increased residue returns to soils, either by increasing nutrient supply, incorporating cover crops in the rotation, or integrating short-term perennial pastures between agricultural periods. A meta-analysis including 31 references, 87 experiments and 146 comparisons was conducted, integrating results from field experiments from national research institutions, extension agencies, and farmer associations, located in different production regions of Argentina. SOC concentrations were harmonized to a 0-30 cm depth, using the splining functions developed by Berhongaray *et al.* (2013). SOC contents 0-30 cm (percent) were converted to stocks (tC/ha) considering the 30-cm depth and soil bulk density (FAO, 2019), and adjusted by equivalent soil mass for the different treatments (considering the minimum observed bulk density of each experiment/field trial; or 1.25 g/cm^3 when no data was provided). Paired data sets were used for SOC stocks comparisons (sustainable vs. conventional practices), and annual rates were estimated considering the duration of each study. Extreme values (± 3 standard deviations) were discarded as outliers.

Improved fertilizer practices generally included medium-term fertilization strategies with N, P and S applications, aimed at replenishing nutrient extraction by crops. Cover crops included oats (*Avena sativa),* rye (*Secale cereale*), triticale (*Secale cereale* × *Triticum aestivum*), ryegrass (*Lolium multiflorum*), hairy vetch (*Vicia villosa)*, common vetch (*Vicia sativa)*, sweet clover (*Melilotus officinalis*), rapeseed (*Brassica napus*), forage radish (*Raphanus raphanistrum*) and different mixtures. The inclusion of permanent pastures generally included 50-50 percent to 75-25 percent crop-pasture rotations, including alfalfa (*Medicago sativa*), tall fescue (*Festuca arundinacea*) or Gatton panic (*Panicum maximum*), depending on the region.

3. Context of the case study

Land use and management of agricultural systems have undergone important transformations in the last decades in Argentina. Agriculture in rotation with pastures was progressively replaced by continuous agriculture with rotations with high frequency of soybeans and winter fallows (Milesi Delaye *et al.*, 2013; Domínguez and Rubio, 2019), and therefore low residue returns to soils. There has been an intense expansion of agriculture at the expense of grasslands, native forests and other natural resources in semiarid, sub-humid and subtropical regions of the country (Volante *et al.*, 2012). Currently, soils of the Chaco-Pampean region exhibit SOC levels between 40-70 percent of the contents of virgin soils (Alvarez and Steinbach, 2009; Sainz Rozas, Echeverria and Angelini, 2011; Milesi Delaye *et al.*, 2013). Recent studies also show a negative balance in soil nutrient levels, due to increased nutrient extraction and low reposition levels. Phosphorus stocks are between 25-60 percent of those of virgin soils, and there has been a steady decrease rate between 1.6-4.4 kg/ha/yr the last decade (Sainz Rozas, 2019). In parallel, extensive research has been carried out during the last decade by national research institutions, extension agencies and farmers associations to promote the use of balanced and adequate fertilizer use strategies, mixed rotations and cover crops, in order to stabilize or raise crop yields, residue returns and SOC stocks in agricultural lands. This study case summarizes much of the available research, including a total of 87 field experiments (Figure 20a). Climatic conditions in the locations considered for this study ranged from 550 to 1 200 mm mean annual rainfall, and from 14 to 22 °C mean annual temperature, covering warm temperate dry, warm temperate moist, tropical dry and tropical moist climatic zones, according to the Intergovernmental Panel on Climate Change climate classification (IPCC, 2019). The study covers different soil orders (USDA Soil Taxonomy): Aridisols, Alfisols, Entisols, Mollisols and Vertisols; with SOC contents 0-30 cm ranging from 23.8 tC/ha to 96.5 tC/ha.

4. Possibility of scaling up

This meta-analysis shows that SOC-oriented practices can be successfully implemented under different climate and soil conditions. In the different regions, farmers have been progressively adopting such practices, especially during the last five years. The use of cover crops is rapidly expanding, mainly as a weed control strategy, and in some regions around 12 percent of the agricultural area is currently including cover crops. At a national level, only 2 percent of the area uses cover crops as a regular practice (AACREA, 2020). Active and site-specific on-farm research and extension is needed, involving farmers as key players, in order to scale these results, and encourage mass adoption of these practices.

5. Impact on soil organic carbon stocks

Practices oriented to increase C returns to soils increased SOC sequestration compared to business as usual practices (Figure 20b). An average SOC sequestration rate of 0.49 tC/ha/yr (± 0.04, Standard error) was observed over all the experiments. Increasing nutrient availability, crop growth and residue returns by increasing fertilizer use showed the lowest rates: around 0.18 tC/ha/yr (± 0.03). The inclusion of cover crops showed average SOC sequestration rates of 0.45 tC/ha/yr (± 0.03). The inclusion of cycles with perennial pastures in crop rotations showed average SOC sequestration rates of 0.76 tC/ha/yr (± 0.03), exhibiting the greatest potential to increase SOC stocks. SOC sequestration results were variable within practices (Figure 20b), especially in the case of cover crops and pastures. Negative values were also observed, meaning that carbon inputs to soils and SOC sequestration in specific cases were lower than business as usual conditions. Years with extremely low precipitations, when water availability was lower in rotations with greater water use such as those including cover crops, may account for these differences. SOC sequestration rates were higher under warm temperate moist climatic conditions compared to dry tropical or dry temperate conditions (Table 117), probably due to the lower biomass production because of lower precipitations. Higher sequestration rates were also observed in soils with baseline SOC contents between 45-55 tC/ha at 0-30 cm. Soils with relatively lower SOC stocks at 0-30 cm (<40 tC/ha) in dry environments or soils with extremely higher SOC stocks at 0-30 cm (>80 tC/ha) showed lower SOC sequestration rates. Overall, SSM practices increased total SOC stocks by 6.8 percent on average by the end of the experiments. Total SOC stocks increased by 2.7 percent with higher fertilizer use, by 4.8 percent with cover crops, and by 10.2 percent with perennial pastures in rotations.

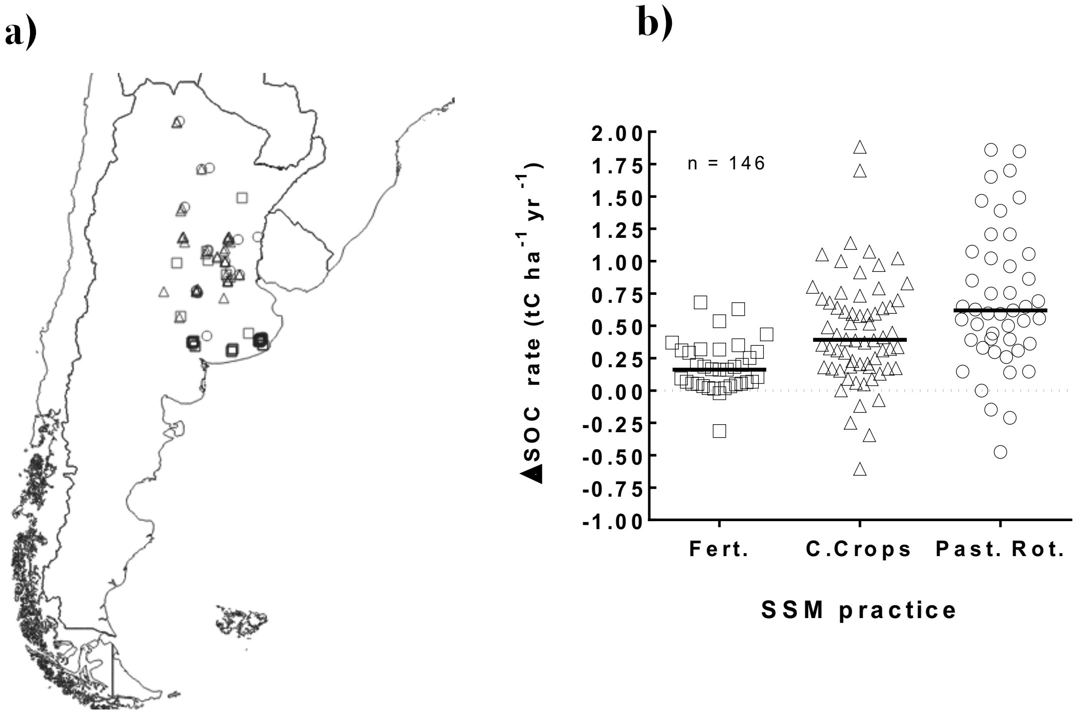

Figure 20. (a) Geographic distribution of the field experiments considered in this study case

(b) Observed annual SOC sequestration rates are shown for three practices: fertilizer use (squares), cover crops (triangles) and inclusion of perennial pastures into crop rotations (circles). Each symbol represents a paired comparison (practice vs. business as usual). Horizontal lines represent the observed median for each practice. Source: Guillermo Peralta, Rodolfo Gil, Belén Agosti, Martin Aciar, Miguel Taboada, Federico Gómez, Matías Schrauf

Table 117. Results from fertilizer use, cover crops and inclusion of perennial pastures in agricultural rotations, across different climatic zones and soil types of Argentina

Average results for each practice (± 1 standard error) are shown

	IPCC Climate zone	Soil type	Baseline C stock at 0-30 cm (tC/ha)	Additional C storage at 0-30 cm (tC/ha/yr)	Duration (Years)	Reference
Fertilizer Use	Warm Temperate Dry	Petrocalcic Paleustoll	37.14	0.05	21	Krüger, Zilio, and Frolla (2017)
	Warm Temperate Dry	Petrocalcic Paleustoll	46.99	0.59	3	Frasier Quiroga, and Noellemeyer (2016)
	Warm Temperate Moist	Petrocalcic Paleudoll	73.52	0.09	11	Landriscini *et al.* (2018)
	Warm Temperate Moist	Typic Argiudoll	50.31	0.24	3	Gudelj *et al.* (2017)
	Warm Temperate Moist	Typic Argiudoll	45.94	0.09	13	Cazorla *et al.* (2017)
	Warm Temperate Moist	Typic Argiudoll	102.39	0.03	7	Domínguez *et al.* (2009)
	Warm Temperate Moist	Typic Argiudoll	93.32	0.31	11	Studdert and Echeverría (2000)
	Warm Temperate Moist	Haplic Kastanozem	29.27	0.5	18	Duval, Martinez and Galantini (2020)
	Warm Temperate Moist	Entic Hapludoll	52.89	0.38	15	Miglierina *et al.* (2000)
	Warm Temperate Moist	Petrocalcic Paleudoll	79.06	0.17	6	Fabrizzi, Moron and García (2003)
	Warm Temperate Moist	Typic Argiudoll	55.88	0.05	6	Restovich *et al.* (2019)
	Tropical Moist	Acuertic Argiudoll	27.88	0.16	8	Mieres (2017)
	Fertilizer use: All experiments		51.4 (± 1.55)	0.18 (± 0.03)		

	IPCC Climate zone	Soil type	Baseline C stock at 0-30 cm (tC/ha)	Additional C storage at 0-30 cm (tC/ha/yr)	Duration (Years)	Reference
Cover Crops	Warm Temperate Dry	Entic Haplustoll	37.00 to 41.00	0.05 to 0.11	19	Álvarez, Giubergia and Basanta (2017)
	Warm Temperate Dry	Entic Haplustoll	36.84 to 40.68	0.13 to 0.17	13	Álvarez (2011)
	Warm Temperate Dry	Paleudol petrocálcico	46.99	1.42	3	Frasier, Quiroga, and Noellemeyer (2016)
	Warm Temperate Dry	Entic Haplustoll	39.2 to 42.2	0.18 to 0.21	5	Peralta, Molina and Solfanelli (2020)
	Warm Temperate Dry to Moist	Argiudoll-Hapludolls-Ustipsaments	30.76 to 48.88	-0.07 to 1.02	2 to 15	Álvarez *et al.* (2016)
	Warm Temperate Moist	Typic Hapludoll	35.81	0.09	10	Constantini (2016)
	Warm Temperate Moist	Typic Argiudoll	45.88	0.2	13	Cazorla *et al.* (2017)
	Warm Temperate Moist	Argic Cromudert	59.6	3.90	3	Girard *et al.* (2018)
	Warm Temperate Moist	Acuic Argiudoll	68.2 to 74.6	-0.85 to 1.00	2	Novelli, Caviglia and Piñeiro (2017)
	Warm Temperate Moist	Typic Argiudoll	50.95	0.32	5	Duval *et al.* (2016)
	Warm Temperate Moist	Typic Hapludoll	47.79	0.26	4	Varela *et al.* (2010)
	Warm Temperate Moist	Typic Argiudoll	30.2 to 34.05	0.18 to 0.68	8	Romaniuk *et al.* (2018)
	Warm Temperate Moist	Typic Argiudoll	53.69	0.48	6	Restovich *et al.* (2019)
	Warm Temperate Moist	Typic/ Vertic Argiudolls	48.05 to 73.08	0.33 to 1.07	6	Agosti, Peralta and Gil (2014); Agosti, Coyos and Gil (2020)
	Tropical Dry	Typic Haplustalf	46.6	0.18	3	Gil (2008)
	Tropical Dry	Typic /Argic Haplustalfs	37.2	0.01 to 0.25	3	Gil, Peralta and Aciar (2016)
	Cover Crops: All experiments		51.73 (± 1.49)	0.45 (± 0.05)		

	IPCC Climate zone	Soil type	Baseline C stock at 0-30 cm (tC/ha)	Additional C storage at 0-30 cm (tC/ha/yr)	Duration (Years)	Reference
Pastures in rotation	Warm Temperate Dry	Petrocalcic Paleustoll	37.38	0.31	7	Krüger, Zilio, and Frolla (2017)
	Warm Temperate Dry	Entic Haplustoll	42.2	0.36	8	Peralta, Molina and Solfanelli (2020)
	Warm Temperate Moist	Typic Hapludoll	35.81	0.62	10	Constantini (2016)
	Warm Temperate Moist	Typic Argiudoll	46.04	0.51	13	Cazorla *et al.* (2017)
	Warm Temperate Moist	Argic Pelludert	67.7	<0.01	7	De Battista *et al.* (2017)
	Warm Temperate Moist	Typic Hapludoll	46.32	0.21	12	Díaz-Zorita, Duarte and Grove (2002)
	Warm Temperate Moist	Typic Hapludoll	48.29	0.23	10	Zanettini, Barraco and Díaz-Zorita (2017)
	Warm Temperate Moist	Typic Argiudoll	94.3	0.94	17	Studdert, Echeverría and Casanovas (1997)
	Warm Temperate Moist	Haplic Kastanozem	32.63	0.14	23	Duval, Martinez and Galantini (2020)
	Warm Temperate Moist	Entic Hapludoll	55.76	0.52	15	Miglierina *et al.* (2000)
	Warm Temperate Moist	Typic Argiudoll	45.02	2.05	7	Álvarez *et al.* (1998)
	Warm Temperate Moist	Acuic Argiudoll	66.6	2.72	6	Novelli *et al.* (2013)
	Warm Temperate Moist	Typic Hapludert	71.6	1.86	6	Novelli *et al.* (2013)
	Warm Temperate Moist	Typic/ Vertic Argiudolls	48.05 to 73.08	0.54 to 0.85	6	Agosti, Peralta and Gil (2014); Agosti, Coyos and Gil (2020)
	Tropical Dry	Typic Haplustoll	51.02	0.33	6	Osinaga, Álvarez, and Taboada (2018)
	Tropical Dry	Typic Haplustalf	46.6	0.62	5	Gil, Peralta and Aciar (2016)
	Tropical Dry	Typic Haplustalf	37.2	0.55	8	Gil, Peralta and Aciar (2016)
	Pastures in rotation: All experiments		47.50 (± 1.23	0.76 (± 0.09)		

6. Other benefits of the practice

6.1. Improvement of soil properties

The inclusion of cover crops or perennial pastures promotes greater and more continuous activity of roots, microorganisms and soil fauna (Acosta-Martinez *et al.*, 2007; Lundgren and Fergen, 2010; Franzluebbers *et al.*, 2014; O'Dea *et al.*, 2015). These practices have shown to improve soil structure, reflected through an increase in aggregate stability, total porosity, macroporosity, hydraulic conductivity, water infiltration, and reductions in bulk density (Villamil *et al.*, 2006; Álvaro-Fuentes *et al.*, 2008; Calonego and Rosolem, 2010; Novelli, Caviglia and Melchiori, 2011; Novelli *et al.*, 2013; Novelli, Caviglia and Piñeiro, 2017).

6.2 Minimization of threats to soil functions

Table 118. Soil threats

Soil threats	
Soil erosion	Cover crops and adequately managed pastures (optimized grazing or cutting frequency and intensity) increase soil cover through the year, reducing wind and water erosion (De Baets *et al.*, 2011).
Nutrient imbalance and cycles	A balanced and judicious fertilizer use strategy replenish nutrients extracted by crops and maintains soil fertility (Abril *et al.*, 2007). Legumes in cover crops or pasture fixate N from the atmosphere and may increase overall N availability in soils (Miglierina *et al.*, 2000). Nitrogen in residues is gradually released, minimizing losses. An increased continuous activity of roots, macro, meso and microorganisms also favors nutrient cycling (Barea *et al.*, 2005). Deep rooted species may act as "catch crops", absorbing nutrients from deep soil layers, and increasing their availability in surface layers (Vos and Van der Putten, 2004).
Soil salinization and alkalinization	By increasing soil residue cover, adequately managed pastures and cover crops reduce water evaporation and capillary rise, reducing the risks of salinization (Gabriel, Vanclooster and Quemada, 2014). Greater water extraction by cover crops and pastures will help to maintain lower water table and stop salinity development in salt affected areas (Gabriel, Vanclooster and Quemada, 2014).
Soil pollution	Integrated crop-livestock systems and cover crops reduce the use of herbicides (Dabney, Delgado and Reeves, 2001; Dhima *et al.*, 2006).
Soil acidification	Increasing carbon inputs to soils have shown to increase organic matter contents, increase cation exchange capacity, reduce exchangeable sodium percentage (ESP), and reduce pH in sodic soils (Diacono and Montemurro, 2015).

Soil threats	
Soil biodiversity loss	Diverse crop rotations with increased carbon inputs to soils can promote more favorable C/N ratio in soils, promote greater biomass and microbial diversity. In general, biodiversity in the soil, not only microorganisms (Acosta-Martínez *et al.*, 2007; Lundgren and Fergen, 2010).
Soil compaction	Cover crops and pastures including tap-rooted species may alleviate soil compaction in specific conditions. High residue cover reduces compressive stress from agricultural machinery (Sasal, Castiglioni and Wilson, 2010). By increasing soil residue cover and increasing aggregate stability, cover crops and adequately managed pastures reduce soil sealing and platy structures, especially in soils with high silt contents in the surface layer (Sasal, Castiglioni and Wilson, 2010).
Soil water management	When adequately managed, cover crops and pastures in agricultural rotations promote greater water use, reduce runoff and deep percolation processes, and increase overall water use efficiency (Sasal, Castiglioni and Wilson; Andrade *et al.*, 2015). Adequate fertilizer use increase crop production as well as residue returns per mm of evapotranspirated water (Grassini, Hall and Mercau, 2009). Thus, greater annual C inputs per mm of available water can be expected with these practices.

6.3 Increases in production (e.g. food/fuel/feed/timber)

Adequate fertilizer use increases grain production and residue returns in agricultural systems. Diverse crop rotations with increased carbon inputs to soils lead to more stable grain production, reducing year to year variation in cash crop yields.

6.4 Mitigation of and adaptation to climate change

The inclusion of diversified cover crops and the inclusion of mixed pastures (legumes and grasses) in rotations have shown to foster soil organic carbon sequestration and reduce CO_2 losses from soils, and reduce N applications from fertilizers, and hence N_2O emissions. Overall, 10-70 percent reductions of CO_2-eq GHG emissions were observed in diversified cropping systems.

6.5 Socio-economic benefits

The use of legume cover crops reduces the nitrogen fertilizer costs in rotations, and herbicides costs during fallows. Lower use of agrochemicals reduces the risks of groundwater pollution and spray drift risks in nearby urban areas.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 119. Soil threats

Soil threats	
Soil erosion	Over grazing pastures or over grazing crop residues by livestock may induce a lower soil cover if not managed properly (Villamil, Amiotti and Peinemann, 2001).
Nutrient imbalance and cycles	More intense crop rotations, especially when combined with livestock production, may increase nutrient extraction if these practices are not in line with an appropriate fertilizer use strategy (Sainz Rozas, 2019).
Soil salinization and alkalinization	Inadequate use of specific mineral fertilizers may increase soil salinity especially in already salt-affected soils (Postiglione, 2002).
Soil contamination / pollution	Inadequate and excessive use of specific mineral fertilizers may increase the risks of groundwater pollution (Perez *et al.*, 2003).
Soil acidification	Inadequate use of ammoniacal fertilizers may increase soil acidification processes (Schroder *et al.*, 2011). An unbalanced nutrient management strategy in more intense crop rotations, especially when combined with livestock production, may induce greater cation extractions and soil pH reductions if not managed properly (Sainz Rozas, 2019).
Soil compaction	Heavy machinery or cattle trampling on moist soils can induce compaction processes if not adequately managed (Frolla *et al.*, 2018).
Soil water management	Water consumption of cover crops has to be monitored and controlled to avoid detrimental effects on cash crops, especially in dry climatic conditions and soils with low water holding capacity (Appelgate *et al.*, 2017).

7.2 Increases in greenhouse gas emissions

Greenhouse gases emissions can be greater in systems with high nitrogen fertilizer applications, linked to greater N_2O emissions (Kahrl *et al.*, 2010), especially in unbalanced rotations that rely exclusively on mineral N applications (e.g. high grass or cereal frequency and low inclusion of legumes). Nitrogen source, rate, timing and placement of fertilizers, and the use of nitrification and urease inhibitors have shown to significantly reduce N_2O emissions and shall be considered among other factors in the fertilization strategy. Enteric CH_4 and other GHG emissions from cattle in mixed systems can be important sources of overall emissions. These emissions will depend on feed digestibility, stocking rates, and cattle management practices among other factors.

7.3 Decreases in production (Food/fuel/feed/timber/fibre

Water and nutrient consumption of cover crops may induce detrimental effects on yields of cash crops, especially in dry climatic conditions, if no appropriate management practices are considered (Appelgate *et al.*, 2017; Marcillo and Miguez, 2017).

8. Recommendations before implementing the practice

A balanced fertilizer use strategy should be implemented, considering application methods, sources, rates, placing and timing, following soil sampling and crop nutrient requirements, in accordance with the International Code of Conduct for the Use and Management of Fertilizers (FAO, 2019). Nitrification and urease inhibitors should be considered whenever possible.

Crop rotations including cover crops should be diverse, including legumes, cereals and other species, in order to reduce N requirements from mineral fertilizers, and reduce pesticide use. Water and nutrient consumption of cover crops should be monitored and adequately managed (e.g. termination timing) to avoid yield reductions in the following cash crops, especially in dry climatic conditions, soils with low water holding capacity, or soils with low fertility. Adequate grazing or cutting intensity and frequencies of pastures and forages should be implemented in mixed systems.

9. Potential barriers for adoption

Table 120. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Water consumption of cover crops may induce detrimental effects on cash crops, especially in dry climatic conditions if not properly managed (Appelgate *et al.*, 2017; Marcillo and Miguez, 2017).
Cultural/Social	Yes	More diverse crop systems require more labor (Lalani *et al.*, 2016). The availability of qualified personnel may be a limiting factor in some areas.
Economic	Yes	Both labor and variable costs are higher (sowing, seeds) when introducing cover crops in rotations. The economic benefits from the reduction in other costs such as herbicide or fertilizer use should

Barrier	YES/NO	
		overcome the costs of implementing these strategies in order to favor mass adoption (Lalani *et al.*, 2016). Livestock facilities (e.g. fences, water facilities) may have been dismantled (following conversion to continuous agriculture; e.g. Viglizzo *et al.*, 2011) or may not be available.
Knowledge	Yes	Active and site-specific on-farm research and extension is needed, involving farmers as key players, in order to scale results, especially in subtropical and warm temperate dry environments.

Photos


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Photo 57. Soils with increased organic carbon stocks and improved soil structure, after 7 years of adopting SSM practices (continuous cover crops), La Matilde, Ines Indart, Argentina

Photo 58. Inclusion of perennials pastures in crop rotations in subtropical climates, Las Lajitas, Salta Argentina

Photo 59. Use of cover crops in crop rotations. Image: Hairy vetch as cover crop, Salto, Argentina

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Photo 60. Inclusion of cover crops in rotations; rye cover crop growing under maize residue, Jesús María, Córdoba, Argentina

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30. Application of swine and cattle manure through injection and broadcast systems in a black soil of the Pampas, Argentina

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1. Related practices and hot-spot

Manure applications; Black soil

2. Description of the case study

The objective of this work was to evaluate the effect of the use of semiliquid swine manure (SM) injected in the surface layer (0-10 cm) and solid cattle manure (CM) broadcasted on the soil surface on the evolution of soil carbon, nitrogen losses, and wheat (*Triticum aestivum*) (winter) yield and foxtail millet (*Setaria italica*) (following summer) biomass. The treatments consisted of the application of different rates of each manure type equivalent to 0 (D0), 50 (D1), 100 (D2) and 150 percent (D3) of the N requirement of each crop. The experiments were carried out sequentially in the same plots in a completely randomized design by triplicate. Gas emission measurements started the day after the manure application and carbon determinations were made at the end of each crop cycle. The N_2O fluxes were determined using vented chambers and the N_2O collected was analyzed with a gas chromatograph. The NH_3 losses were determined using static semi-open chambers. The NH_3 produced was collected by distillation in 2 percent boric acid until completing a volume of 35 mL.

3. Context of the case study

The experiments were conducted in a silty-loamy Typic Argiudoll (Mollisol) (clay 265 g/kg, silt 705 g/kg, fine sand 30 g/kg), which is one of the main soils in the Pampas region of Argentina. The farm is located near to El Trébol city (60 60° 43.13′ W, 30° 10.10′ S 43.13′ W, 30 60° 43.13′ W, 30° 10.10′ S10.10′ S), Argentina. The climate is mesothermic humid, with annual isohyets varying from 900 to 1 100 mm. The average maximum temperature of the warmest month is 32 °C and the average minimum temperature of the coldest month is 7 °C. The farm develops agricultural and livestock activities, specifically intensive production of cattle and swine, which generate large volumes of manure. The experiments were carried out in a field that was under an agricultural rotation of corn (*Zea mays*)/wheat (*Triticum aestivum*)/soybean (*Glycine max*)/wheat/foxtail millet for four years. Here, the variation of carbon stock during the wheat/foxtail millet phases of the rotation (i.e. from pre-sowing wheat to after harvesting foxtail millet) are presented. The experiments were part of the Research Project FONARSEC 2013/28, financed by the National Agency for Scientific and Technological Promotion, Ministry of Science, Technology and Productive Innovation of Argentina.

4. Possibility of scaling up

The practice described here is commonly applied on the farm (500 ha) where the experiments were carried out. Thus, the scaling up to other commercial farms is possible.

5. Impact on soil organic carbon stocks

Determinations carried out at the end of the wheat and foxtail millet cycles showed that soil organic matter (OM) and carbon (C) stock increased after the application of both manure types (Table 121).

Table 121. Values of soil organic matter and carbon stock in the wheat *(Triticum aestivum)* and foxtail millet *(Setaria itálica)* experiments for different application rates of semiliquid swine manure (SM) and solid cattle manure (CM)

Application rates (% of required N)	Wheat				Foxtail millet			
	SM	CM	SM	CM	SM	CM	SM	CM
	Organic matter (g/kg)		C stock (t/ha)		Organic matter (g/kg)		C stock (t/ha)	
D0 (without manure) (Baseline)	33.3	33.3	23.1	23.1	33.3	33.3	23.1	23.1
D1 (50%)	33.8	35.2	24.2	24.6	34.5	36.1	24.5	25.3
D2 (100%)	35.1	36.8	25.1	26.3	35.8	37.8	25.4	27.1
D3 (150%)	36.2	40.4	26.0	30.7	37.8	42.1	27.3	32.0

The increment in the C stock after each manure application in the wheat experiment ranged from 1.1 to 2.9 t C/ha, and from 1.5 to 7.6 t C/ha for SM and CM, respectively. On the other hand, the net increment in the C stock in the foxtail millet experiment (i.e. plus over the values measured at the end of the wheat cycle) ranged from 0.3 to 1.3 t C/ha, and from 0.7 to 1.3 t C/ha for SM and CM, respectively. Values of C stock were corrected according to a soil bulk density value of 1.35 t/m^3 for making the treatments comparable. Our results showed that the application of both type of manure on two consecutive crops can increase carbon sequestration and, simultaneously, crops productivity (see section 6.3). However, the potential of C sequestration of the CM was greater than that of the SM.

6. Other benefits of the practice

6.1 On soil properties

The increase of SM and CM rates improved soil quality in both wheat and foxtail millet crops. In both experiments, pH values remained unchanged with the increase in manure rates (Figure 21 and Figure 25). Cation exchange capacity (CEC) and hydraulic conductivity (Ks) increased with the increase in manure rates in both SM (Figure 22 and Figure 24) and CM (Figure 26 and Figure 28) experiments. On contrary, soil bulk density decreased in SM (Figure 23) and CM (Figure 27). Soil resistance to root penetration also decreased. As a result, the least limiting water range (i.e. the range in soil water content after rapid drainage has ceased within which limitation to plant growth associated with water availability, soil aeration and soil resistance to root penetration are minimal) increased with the increase in manure rates in both SM and CM experiments (unpublished data).

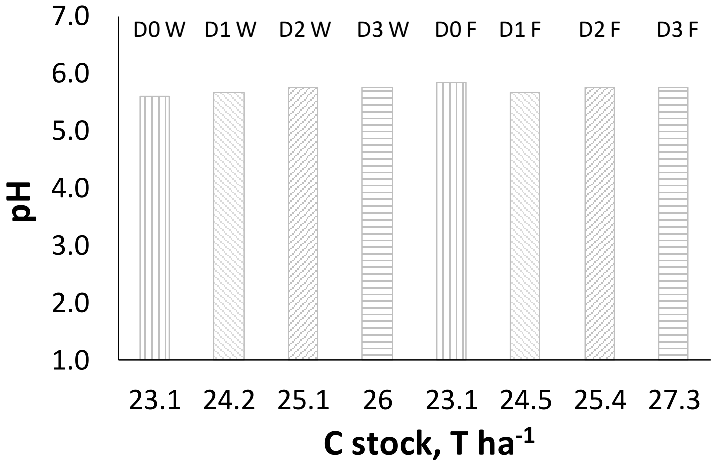

Figure 21. Values of pH as a function of C stock (t/ha); D0, D1, D2, D3: semiliquid swine manure rates; W: wheat; F: foxtail millet

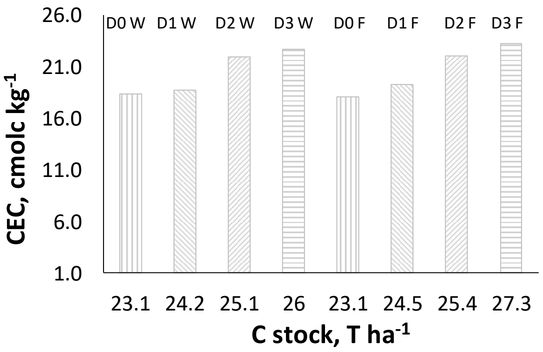

Figure 22. Values of cation exchange capacity (CEC) as a function of C stock (t/ha); D0, D1, D2, D3: semiliquid swine manure rates; W: wheat; F: foxtail millet

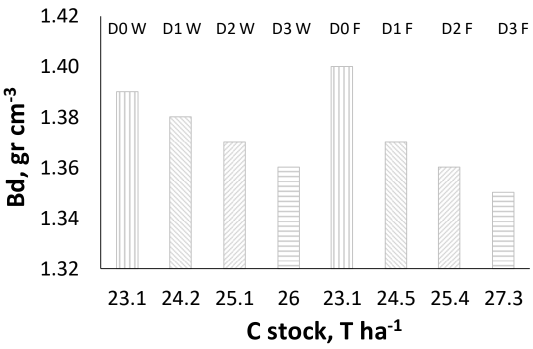

Figure 23. Values of soil bulk density (Bd) as a function of C stock (t/ha). D0, D1, D2, D3: semiliquid swine manure rates; W: wheat; F: foxtail millet

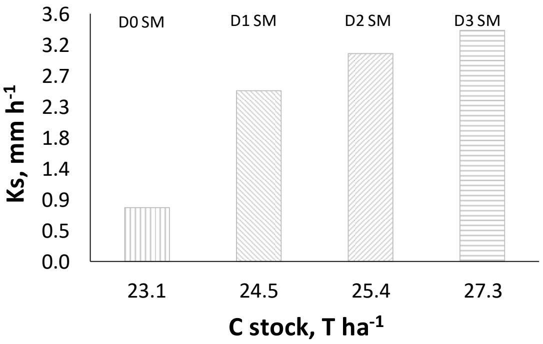

Figure 24. Values of hydraulic conductivity (Ks) as a function of C stock (t/ha). D0, D1, D2, D3: semiliquid swine manure rates; W: wheat; F: foxtail millet

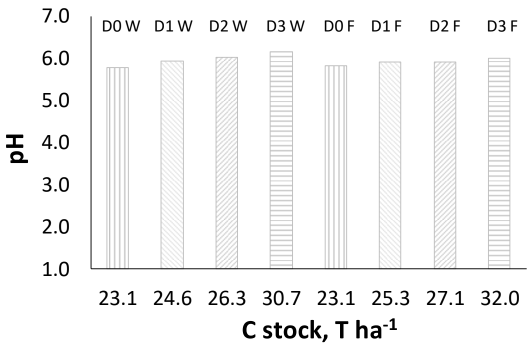

Figure 25. Values of pH as a function of C stock (t/ha). DO, D1, D2, D3: solid cattle manure rates; W: wheat; F: foxtail millet

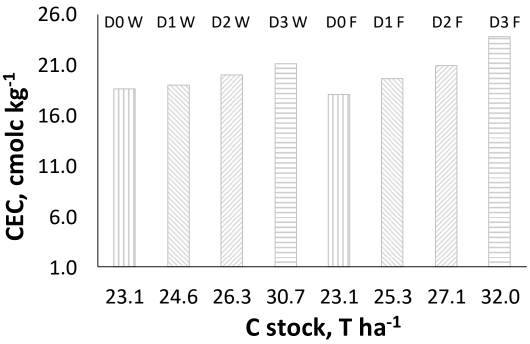

Figure 26. Values of cation exchange capacity (CEC) as a function of C stock (t/ha). DO, D1, D2, D3: solid cattle manure rates; W: wheat; F: foxtail millet

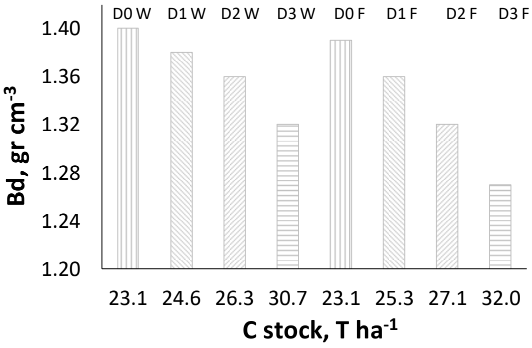

Figure 27. Values of soil bulk density (Bd) as a function of C stock (t/ha). DO, D1, D2, D3: solid cattle manure rates; W: wheat; F: foxtail millet

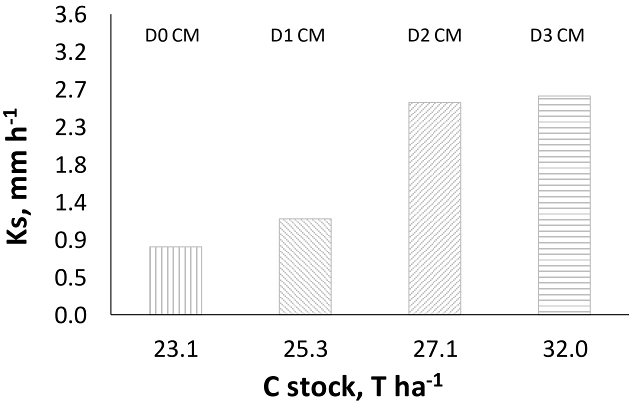

Figure 28. Values of hydraulic conductivity (Ks) as a function of C stock (t/ha). D0, D1, D2, D3: solid cattle manure rates; W: wheat; F: foxtail millet

The carbon stock varied with the type of manure and application system. The amount of organic carbon added with CM was greater than that added with SM. Soil properties improvement was more noticeable in CM than in SM, which may be associated with the greater amount of organic matter added with CM. This difference may explain the greater increase in CEC (also in macro and micronutrients, unpublished data) and the more noticeable decrease in Bd. On the other hand, soil disturbance by the injection system could be responsible for the higher values of Ks in SM. Our results confirm the findings of other authors (Ferrera et al., 2006; Ozlu, Kumar and Arriaga, 2019; Rasoulzadeh and Yaghoubi, 2010; Zavatarro et al., 2017). Figure 29 shows the soil structure types in the plot without cattle manure (WM, on the left) and with CM (on the right). The sub-angular blocky structure type predominates in the former, while the granular structure type predominates in the latter. The most notable difference was found from 0 to 25 cm soil depth

Figure 29. Typic Argiudoll without and with application of cattle manure

6.2 Minimization of threats to soil functions

Table 122. Soil threats

Soil threats	
Soil erosion	The addition of both manure types increases crops production and, consequently, the amount of plant residues on the soil surface that protects it from erosion (Anwar *et al.*, 2018).
Nutrient imbalance and cycles	Manure contains important amounts of macronutrients, especially N, P and K, and micronutrients that help to compensate soil nutrients losses as grains and animal products. Nutrient recycling can be enhanced through manure addition, which is compatible with other conservation practices, such as the use of adequate crop rotations (Sheldrick, Keith Syers and Lingard, 2003).
Soil contamination / pollution	Manure application to the soil according to the agronomic fertilization criteria (i.e. the amount of applied manure is based on crop needs, soil characteristics, and weather patterns) contributes to reduce pollution in places where waste accumulates (Harris *et al.*, 2020).
Soil acidification	Manure contains important amounts of calcium and magnesium that may reduce soil acidification. Also, manure increases soil organic matter that improves the soil buffer capacity. As a consequence, plant growth is less affected when certain elements, such as iron, manganese, sodium, are present in amounts slightly higher than ideal (Ano and Ubochi, 2007).
Soil biodiversity loss	Generally, bacterial and fungal biodiversity and biomass in the soil is increased with manure application. Earthworm biomass, number and density is also increased (Ferrera *et al.*, 2006; Zavatarro *et al.*, 2017).
Soil sealing	Soil sealing is reduced by adding manure with high carbon content because it improves soil aggregation and stability, which reduces the destructive impact of the raindrops (Mikha and Rice, 2004).
Soil compaction	Soil compaction is reduced because manure causes a reduction of soil bulk density and soil resistance to root penetration (Rasoulzadeh and Yaghoubi, 2010; Imhoff *et al.*, 2014; Ozlu *et al.*, 2019).
Soil water management	Soil water availability is increased because manure increases soil total porosity and the amount of mesopores that retain water. Also manure increases soil macropores allowing a greater water infiltration (Imhoff *et al.*, 2014; Zhang *et al.*, 2017).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Our results showed that both manure types increased the productivity of wheat and foxtail millet and, simultaneously the soil carbon stock. For wheat and SM, the optimal dose of N was 130 kg/ha, with a grain yield of 5 820 kg/ha. For wheat and CM, the optimal dose of N was 136 kg/ha, with a grain yield of 5 810 kg/ha. For foxtail millet and SM, the optimal dose of N was 330 kg/ha, with a dry biomass production of 14 960 kg/ha. For foxtail millet and CM, the optimal dose of N was 309 kg/ha, with a dry biomass production of 13 955 kg/ha. The optimal rate of N and the achieved production were similar for both types of manure, which confirms the benefits of using the agronomic fertilization criteria independently of the type of manure.

6.4 Mitigation of and adaptation to climate change

The application of SM and CM increased the emission of NH_3 (Figure 30, Figure 31). The emission curves were similar in winter (wheat) and summer (foxtail millet) for rate 0 (D0) in both experiments. In the SM experiment, for rate 3 (D3), the NH_3 emission increased after the manure application, although it was notably higher in summer, highlighting the influence of the temperature on N-NH_3 losses. Gas emission stabilized around the thirteenth day after the application in both seasons. In the CM experiment, for rate 3 (D3), the NH_3 emission increased slightly after the manure application, with little difference between summer and winter. Gas emission stabilized around the ninth day after the application in both seasons. The results indicate that the losses of NH_3 depended on the type of manure and the weather season whereas the time elapsed until the NH_3 emission stabilizes and decreases mainly depended on the type of manure.

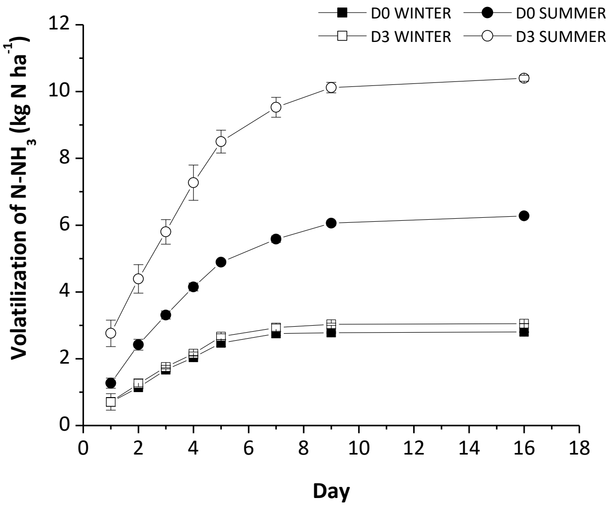

Figure 30. Cumulative values of N-NH3 lost by volatilization from the semiliquid swine manure experiment. Bars are the standard error of each individual point

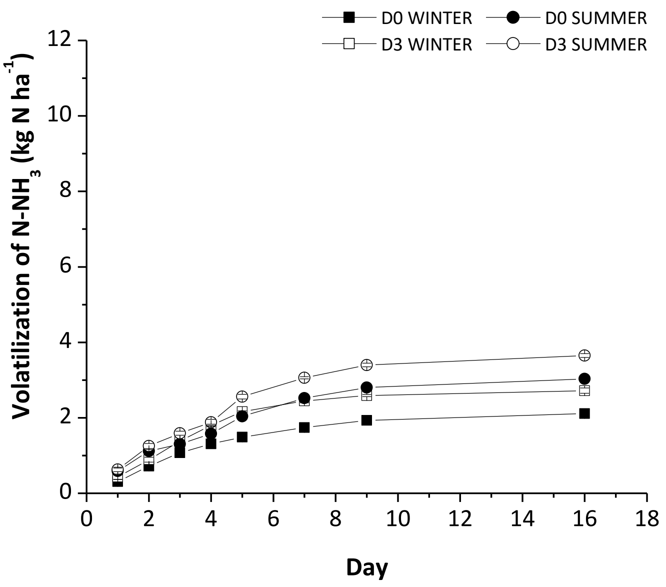

Figure 31. Cumulative values of N-NH_3 lost by volatilization from the solid cattle manure experiment. Bars are the standard error of each individual point

6.5 Socio-economic benefits

The nitrogen loss was greater when SM was applied in summer. Results show that the higher the temperature, the greater the loss of N, especially when manure contains nitrogen integrating simple molecules (NH_4^+ or NO_3^- for example). Therefore, to increase socio-economic benefits and to decrease air pollution, manure should be applied during climatic seasons with lower temperature, especially for those manure types that contain N integrating simple molecules.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 123. Soil threats

Soil threats	
Soil erosion	Soil losses can be enhanced if manure causes soil dispersion and degradation (Cherobim *et al.*, 2017).

Soil threats	
Nutrient imbalance and cycles	Manure addition increases the soil nutrient´s content. However, depending on the manure composition, it may cause a disequilibrium in the nutrient content. For example, CM contains a lot of phosphorus (P), thus if manure is applied according to the crop nitrogen need, P in the soil may reach such high content that it begins to reduce the availability of other nutrients (Lopes do Carmo *et al.*, 2016).
Soil salinization and alkalinization	The amount of sodium and salts depends on the type of manure and water composition. Thus, for manure application, the amount of sodium or salts contained in the manure has to be taken into account to avoid soil salinization and alkalinization, which affect plant growth (Ould Ahmed *et al.*, 2010; Lopes do Carmo *et al.*, 2016).
Soil contamination / pollution	The amount of phosphorus and nitrogen-NO3- in the manures is very variable, and sometimes very higher. Applying excessive amounts of manure can produce nutrients losses by leaching and volatilization resulting in groundwater and air pollution (Cherobim *et al.*, 2017).
Soil acidification	Manure has variable pH depending on its composition. Liquid y semiliquid manure may have pH > 7. Applying excessive amounts can produce an excessive increase in soil pH, which may affect the availability of some soil nutrients (Lopes do Carmo *et al.*, 2016).
Soil biodiversity loss	Excessive and repeated applications of the same manure can cause changes in the microorganisms community and, sometime, the loss of some groups of (van der Bom *et al.*, 2018; Chen at al., 2020).
Soil sealing	Sprinkling excessive amounts of liquid manure containing high sodium content may cause soil surface dispersion and sealing (Cherobim *et al.*, 2018).
Soil compaction	Adding excessive amounts of manure containing high sodium content may cause soil structure degradation, loss of structure stability, and, as a consequence, soil densification. Also, machinery used to apply manure can produce soil compaction (Rauber *et al.*, 2018).
Soil water management	Soil water management may be hindered if the addition of manure causes degradation of the soil structure. Application rates should not exceed the soil water storage capacity to avoid resources pollution and erosion (Zhang *et al.*, 2017).

7.2 Increases in greenhouse gas emissions

The application systems and the type of manure have significant influence on N_2O emissions. Also, N_2O emissions depend on the climate (Antille *et al.*, 2015). In our experiments, the higher N_2O emission was recorded when SM was applied in summer, which highlights the remarkable effect of the temperature (average ≈ 32 ° C) on gas emission. In addition, greater differences in the soil water-filled pore space (WFPS) between the experiments (SM and CM) were determined in summer. During the first five days of the study, the average value of soil WFPS was 0.49 m^3/m^3 in SM and 0.34 m^3/m^3 in CM. Thus, the higher temperature and greater WFPS may explain the higher N_2O emission in the SM experiment. The N_2O emission, expressed as Ceq., indicates that about 300 kg/ha of carbon were lost to the atmosphere in summer contributing to the climate change (Figure 32).

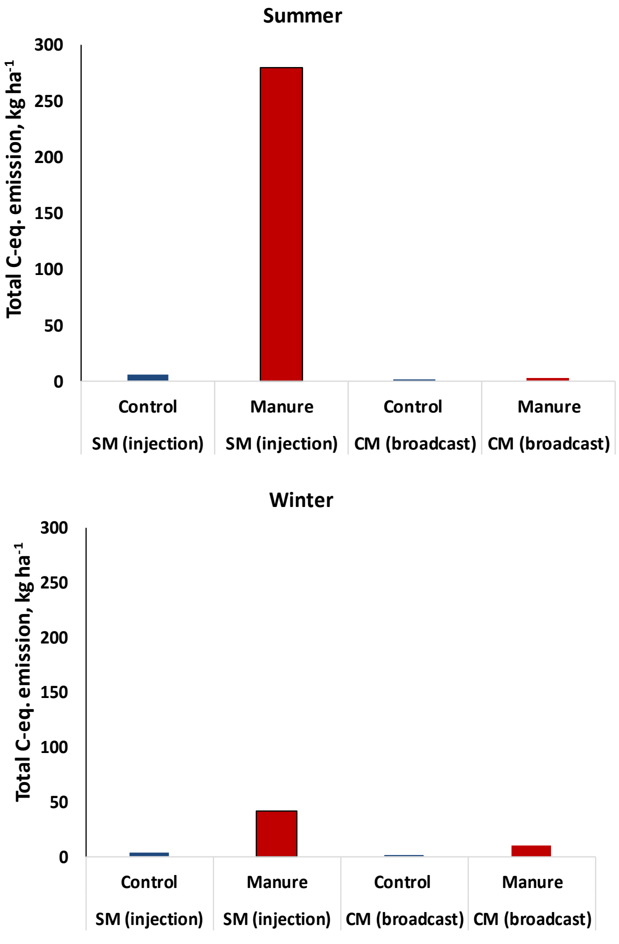

Figure 32. Nitrous oxide emission expressed as total Ceq. Emission

For the application of semiliquid swine manure (SM) and soil cattle manure (CM) in summer and winter in the control (without addition of manure) and with manure (D3= 150 percent of the nitrogen required for foxtail millet in summer and wheat in winter) treatments

During winter, the higher N_2O emission was also recorded in the SM experiment, but losses were lower than 50 kg C/ha. This finding may be explained by the lower temperature (average ≈ 7 ° C) and the lower values of WFPS (≈0.24 m^3/m^3) measured in winter. Moreover, the amounts of N-N_2O lost in both experiments were very different, which can be attributed to the different chemical composition of the manures.

8. Recommendations before implementing the practice

Adding SM and CM is a useful practice to enhance soil chemical and physical properties, and simultaneously crops production. However, it is very important to define the adequate manure rates taking into account the nutrient requirements of the crops, the nutrient supply of soils, the climate characteristics, and the chemical and physical characteristics of the manure in order to avoid soil, water and air pollution.

9. Potential barriers for adoption

Table 124. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Manure application in inadequate rates can increase GHG emissions as well as pest and diseases (Zavatarro *et al.*, 2017). Also, the incorrect management of manure can cause sediment and nutrients losses associated to runoff (Cherobim *et al.*, 2017).
Cultural	Yes	People from cities may have a different understanding on the need of recycling nutrients through the manure use because of lack of information and concerns about pollution (Maisonnave *et al.*, 2014).
Social	Yes	People can show resistance to changing their system of manure application, which is mainly by sprinkling in Argentina.
Economic	No	Manure use can substitute mineral fertilizer, reducing production costs (Zavatarro *et al.*, 2017).
Institutional	No	No information is available.
Legal (Right to soil)	Yes	Some laws regulate the use of manure (Oenema, 2004).
Knowledge	Yes	There is lack of knowledge about the advantages and risk of using manure to recycle nutrients in the fields and, simultaneously, to reduce contamination for different situations (soil types, climate, relief, manure types, etc.) (Zavatarro *et al.*, 2017).
Natural resource	No	There are several resources types (manure) that can be used.

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31. No tillage and cover crops in the Pampas, Argentina

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1. Related practices and hot-spot

No-till, cover cropping; Black soils

2. Description of the case study

This study case is based in the Pampas in Argentina, a vast plain of around 60 million hectares, considered as one of the most important grain producing regions in the world. Three meta-analysis were used for this chapter that integrate results from numerous experiments of no-till (Steinbach and Alvarez, 2006; Alvarez and Steinbach, 2009) and cover crops management (Alvarez *et al.*, 2017), together with some other research in the Pampas.

A meta-analysis was done to integrate results from numerous experiments of short, medium, and long-term periods under no-till management in Steinbach and Alvarez (2006). This review used data from experiments done under experimental designs, using machinery and practices commonly used by farmers, and SOC mass could be calculated to the depth (equal to or deeper than tillage depth). On an equivalent mass basis, 42 paired data sets were used for SOC comparisons of no-till vs. plow till (moldboard plow or disk plow). Another review compiled results produced in 35 field experiments along the Pampas to determine the effect of no-till systems on some soil physical properties, water content, nitrogen availability or crops yield (Alvarez and Steinbach, 2009).

Results of 67 local field experiments with winter cover crop effects on soils and crops were analyzed in Alvarez *et al.* (2017). The majority of the tested graminaceous cover crops were rye (*Secale cereale*), oat (*Avena sativa*), triticosecale (*x Triticosecale*), ryegrass (*Lolium multiflorum*), barley (*Hordeum vulgare*) and rescue grass (*Bromus unioloides*). Legumes cover crops were hairy vetch (*Vicia villosa*) and common vetch (*Vicia sativa*).

3. Context of the case study

The Pampas Region is an extensive prairie that occupy some 22 percent of Argentina. Mean annual temperature ranges from 19 °C in the north to 12 °C in the south, and mean annual rainfall varies from 500 mm in the west to 1100 mm in the east. Soils of the region were developed over eolian-loessic type sediments and the predominant order is Mollisols. Cultivation in the Pampas began by the last quarter of the 19th century and is occupying 50 percent of the surface at present. Low-input agriculture, in combination with livestock production, was performed till 1970; afterwards soybean crop was introduced. This crop replaced pastures and at present it accounts for 60 percent of the seeded area of grain crops. A widespread adoption of no-till occurred since 1990 and nowadays almost 95 percent of agriculture is under no-till in the Pampas. The public sector (researchers and extension units) as well as the associated manufacturing industries (farm machinery, seeds, and agrochemicals) played a key role in establishing a new agricultural production strategy based no-till farming. The no-till association (AAPRESID) as a consolidated network, brought together all relevant stakeholders to share technical and economic information and to promote the benefits of the no-till and cover crops technology. However, there is currently an ongoing debate regarding the possible negative impacts of no-till in marginal areas not suited for cultivation. The northern part of Argentina has experienced a major shift in farming systems from (more sustainable) livestock production to relatively intensive (and less sustainable) cropping systems.

Cover crops are a valuable management option for reducing soil erosion and nitrogen losses from agroecosystems. They improve soil quality but the impacts on crop yield depend on the type of cover crop, the commercial crop considered and the climate. In the Argentine Pampas the introduction of cover crops in rotations is being extensively studied by official institutions. Winter cover crops are being adopted by farmers gradually and many experiments were performed by official institutions to evaluate their suitability as a common production practice. Here we reviewed the effect of no-till and cover crops as agricultural practices implemented in rainfed agriculture at commercial scale in the Pampas for SOC sequestration.

4. Possibility of scaling up

Almost 95 percent of agriculture is under no-till in the Pampas, there is no data on how much of agriculture uses cover crops. Although, no-till and cover crops management is expanding to other regions and to different crops (i.e. horticulture: Bondía *et al.,* 2014; Caracotche, Bondia and Vanzolini, 2014; D´Amico, Varela and Bellaccomo, 2016).

5. Impact on soil organic carbon stocks

The no-till review showed that carbon increases between 3 percent and 15 percent in the topsoil (0-20 cm) in the long term (Steinbach and Alvarez, 2006). Average over the experiments a 2.76 t/ha SOC increase was observed in no-till systems compared with tilled systems (Table 125). The largest increases corresponded to soils from the semiarid portion of the region, and the SOC under tillage explained most of the SOC variation under no-till ($R^2 = 0.94$). The conversion of the whole Pampas cropping area to no-till would increase SOC by 74 MtC, about twice the annual C emissions from fossil fuel consumption of Argentina (40 MtC/yr; CIA World Factbook, 2004). The review of field experiments with winter cover crop reflect that SOC content of the 0–20 cm layer rose ca. 4 percent in fine-textured soils and 9 percent in coarser ones (Alvarez *et al.*, 2017).

Table 125. Evolution of SOC stocks at 0-20 cm depth in no-till systems of the Pampas

Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Year)	More information: number of studies included for the given soil type/climate
Warm Temperate Dry	Entic Haplustoll	39.2	0.33	6.3	3 cropland experiments
Warm Temperate Moist	Haplustol	34.8	3.15	4	2 cropland experiments
Warm Temperate Moist	Luvic Phaozem	78.2	2.14	5	1 cropland experiment
Warm Temperate Moist	Pretrocalcic Argiudoll	67.8	0.48	6	1 cropland experiment
Warm Temperate Moist	Pretrocalcic Paleudoll	51.7	0.71	7	2 cropland experiments
Warm Temperate Moist	Typic Argiudoll	46.7	0.48	8.2	36 cropland experiments
Warm Temperate Moist	Typic Hapludoll	35.6	1.86	5	1 cropland experiment
Warm Temperate Moist	Typic Haplustoll	50.5	1.50	7.7	3 cropland experiments

Source: Data from Steinbach and Alvarez (2006)

6. Other benefits of the practice

6.1. Improvement of soil properties

No-till has been an effective solution to the problem of soil erosion in the Pampas and is meant to keep soil in its place and keep the top layer, which is the most fertile fraction. Soil physical properties improved after cover crops. Bulk density was minimally affected, structural stability and water infiltration increased, while soil penetration resistance decreased. Nitrate-N decreased after cover crops by 30 percent regardless of the cover crop species was or was not legume (Alvarez *et al.*, 2017).

6.2 Minimization of threats to soil functions

Table 126. Soil threats

Soil threats	
Soil erosion	No till and cover crops increase surface plant residues, which prevent from wind erosion and water runoff (Buschiazzo, Zobeck and Abascal, 2007).
Nutrient imbalance and cycles	Legume cover crops increase soil nitrogen, incorporation of N via atmospheric fixation; while grass species tend to reduce available nitrogen, and used for the retention of nutrients (catch crop).
Soil salinization and alkalinization	Cover crops are used to keep salty water tables at low levels by increasing water consumption.
Soil contamination / pollution	Cover crops are used for reduction of weeds by competition, reducing the use of herbicides.
Soil biodiversity loss	No-till increase the biodiversity of soils (Gomez *et al.*, 2007).
Soil compaction	The incorporation of organic matter (green manure) or high root biomass from cover crops are used for the decompaction of the soil.
Soil water management	No-till increase soil available water (Dardanelli, 1998). Cover crops are used to consume water to reduce flooding or providing soil cover to reduce evaporation.

6.3 Increases in production (e.g. food/fuel/feed/timber)

Soybean yield was not affected by tillage system, but wheat and corn yields were lower under no-till than under plow tillage without nitrogen fertilization (Alvarez and Steinbach, 2009). Corn yield increased by 7 percent after legume species cover crop as compared to a fallow (Alvarez *et al.*, 2017).

6.4 Mitigation of and adaptation to climate change

No-till system reduces fuel consumption as compared to plow tillage, in line with international efforts to reduce fossil fuel consumption, this represents a C saving of 24 to 61 kgC/ha/yr (West and Marland, 2002). Cover crops increase C inputs to the soil.

6.5 Socio-economic benefits

No-till and cover crops may have positive socio-economic benefits. The use of legume cover crops reduces the nitrogen fertilizer costs in cereals, increasing the profit up to 10-15 percent (Capurro *et al.*, 2011). Grass cover crops reduce the need for herbicides and other pesticides, reducing cost but also by helping safeguard personal health. No-till also prevent soil erosion so reducing the risk of floods while protect water quality for farms and cities.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 127. Soil threats

Soil threats	
Nutrient imbalance and cycles	Nutrients become highly stratified near the soil surface under no-till (Diaz-Zorita, Barraco and Alvarez, 2004). This might produce a shallow root system. The level of nitrate in soils is significantly lower (-21 kg N/ha) under no-till, reaching to differences as high as 60–80 kg N/ha when comparing with conventional tillage (Alvarez and Steinbach, 2009). No-till generates the necessity of increase nitrogen fertilizers utilization in graminaceus crops.

Soil threats	
Soil contamination / pollution	No-till increased the use of herbicides and their persistence in soils. Cover crops are used also to compete with weeds and to reduce the use of herbicides under no-till, nevertheless the use of cover crops under no-till is still limited.
Soil acidification	Increases of acidity in surface layers of soils under no-till have been widely reported and are usually associated with the acidifying effect of nitrification of ammoniacal fertilizers and the decomposition of crop residues.
Soil compaction	Wheel traffic of heavy machinery over moist soils, especially at harvest can cause substantial compaction to a depth of 20-30 cm and sometimes deeper (Botta *et al.*, 2018).
Soil water management	Cumulative water content to 2m depth decreased by around 20 percent with cover crops (Alvarez *et al.*, 2017).

7.2 Increases in greenhouse gas emissions

Emissions of N_2O were greater under no-till with a mean increase of 1 kg N/ha/yr in denitrification rate for humid pampean scenarios (Steinbach and Alvarez, 2006). Results from Alvarez *et al.* (2013) showed that corn crops under no-till produce higher N_2O emissions than soybean crops due to N fertilization. The increased emissions of N_2O might overcome the mitigation potential of no-till due to C sequestration in about 35 years, and therefore no-till might contribute to global warming. So far, no research has been done in the Pampas about the effect of cover crops on greenhouse gas emissions. However, grass cover crops tend to reduce available nitrogen and increase soil physical properties, and this could reduce denitrification processes under no-till.

7.3 Conflict with other practice(s)

No-till conflict with conventional tillage practice, which it is used by farmers for soil aeration and decompaction. No-till increase bulk density by 4 percent in comparison to conventional tillage, and cone penetration increased by 50 percent in many soils (Alvarez and Steinbach, 2009). The increase of bulk density is greater in soils of initial low bulk density.

7.4 Decreases in production (Food/fuel/feed/timber/fibre

When comparing yields of summer crops after fallow or cover crops, soybean yield was little affected (~2 percent) by the cover crop (usually grass cover crop), while corn yield tended to decrease when the cover crop was a non-legume (- 8 percent) or significantly increased after legume species (+7 percent).

8. Recommendations before implementing the practice

- Residues of no-till cereal crops are best handled by chopping and spreading very evenly at harvesting.
- It is recommended to have variability in the quantity of aboveground crop residues and roots in soil profile. Increasing in cropping frequency and crop diversity, such as double crops rotation, can produce more roots and reduce possibilities of soil compaction.
- Use cover crops with no-till in order to reduce the need of herbicides and nitrogen fertilizers.

9. Potential barriers for adoption

Table 128. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	In water-limited areas the adoption of these practices may be hampered because of competition problems for water and nutrient between the ground covers and the main crop (Cooper *et al.*, 2016).
Cultural	Yes	The adoption of no-till was possible due to the rapid adoption of transgenic crops - soybean, maize, and cotton (Pengue, 2005). Herbicide-resistant crops were needed to change from plowing to chemical weed control.
Social	Yes	No-till adoption in Argentina significantly increased the use of pesticides, this brought rejection in much of society, and increased social conflicts against the no-till model of production. (García-López and Arizpe, 2010).
Economic	Yes/No	No-till requires a significant investment in new machinery for their effective implementation (Trigo *et al.*, 2009), which could make the technology not directly applicable to small farming and familiar subsistence agriculture.

Barrier	YES/NO	
		However, planting, spraying and harvesting operations are contracted in most Argentinean farms, achieving huge efficiencies in the use of machinery and making operations cheaper for farmers. Cover crops includes the direct cost for sowing, normally uses low technology (broadcast seeding) and can be done by hand for small areas or mechanically for relatively large areas. Species and cultivar used for cover crops are of low economic value and frequently self-produced seeds. These costs might be overcome by its benefits, as the reduced herbicides and/or tillage cost for weed control.
Knowledge	Yes	No-till substantially change crop management (weeds pest control, fertilization). New knowledge needs to be created locally to adopt this practice.

Photos

Photo 61. Corn under no-till system and cover crops seeded with airplane before corn harvest in March 2020

Photo 62. Cover crop Vicia villosa for weed control and nitrogen fixation previous to sow maize in spring 2019

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32. Increasing yield and carbon sequestration in a signalgrass pasture by liming and fertilization in São Carlos, São Paulo, Brazil

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1. Related practices

Liming, no-till, mineral fertilization; Grassland

2. Description of the case study

This study case aimed to evaluate the impact of liming and mineral fertilization of a Signalgrass pasture on C accumulation in surface and deeper layers of a Brazilian Oxisol. A 27-yr old Signalgrass pasture ((*Urochloa decumbens* cv. Basilisk Stapf (Syn: *Brachiaria))* was used in the trial. This pasture has been grazed in a stocking rate of one animal per ha and did not receive any liming and fertilizer until the beginning of the experiment. Treatments used in a 6-year trial are described in Table 129, and both limestone and fertilizers were applied to the soil surface with no soil plowing or disc-harrowing. Soil C stocks were calculated in equivalent soil mass, taking the native *Cerrado* (Savanna forest) soil mass as reference. Limed soil (0-100 cm) under non-fertilized pasture showed an annual increase of 1.71 tC/ha after 6 years over the soil under native vegetation. In contrast, fertilization of low productive and degraded pasture resulted in C accumulation rates varying from 5.4 to 7.2 t/ha/yr. The results illustrate that despite the C saturation in the surface soil layer, as evidenced by a sigmoid relationship between C contents in the whole soil and the clay fraction through the soil profile, the large proportion of C accumulation (from 55 to 68 percent) in deeper soil layers makes tropical pasture soils suitable long-term C sinks.

Table 129. Treatments applied to a Signalgrass pasture

Treatments	Description
T00	Control, without liming and fertilizer
T0f€	No lime and fertilizer (200 kg/ha/yr N - ammonium sulfate, and 200 kg/ha/yr K_2O - KCl)
T2f€	Liming (2 t/ha in the first year plus 1 t/ha/yr in the second year) and fertilizer (200 kg/ha/yr N - ammonium sulfate, and 200 kg/ha/yr K_2O -KCl)
T4wf€	Liming (4 t/ha in the first year) and fertilizer (200 kg/ha/yr N - ammonium sulfate, and 200 kg/ha/yr K_2O -KCl)

€ Treatments also fertilized with single superphosphate (18% P2O5) to raise P in the soil to 10 mg/dm3.

3. Context of the case study

The studied area is located in the municipality of São Carlos, State of São Paulo, Southeastern Brazil (21°58'15.6" S and 47° 50' 55.33" W), 893 m above sea level. The prevailing climate is Cwa, following the Koeppen classification, and Tropical Moist according to the IPCC, with a mean annual temperature of 20°C and an average annual rainfall of around 1 360 mm. The soil is an Orthic Ferralsol according to FAO classification System (Hapludox, after US Soil taxonomy, and Red Yellow Latosol after the Brazilian Classification System (Calderano Filho *et al.*, 1998)), with 320 g/kg clay, and fragile structural stability. The native vegetation is considered an ecological transition zone, due to the occurrence of *Cerrado* (Savanna forest) and Mesophyle Semideciduous forest vegetation, a hardwood dry forest mainly driven by soil fertility and climate.

4. Possibility of scaling up

Liming and fertilization are essential issues to control soil acidity and lack of nutrients and improve pasture yield and quality. The practice of liming is commonly applied to crops, but for a long time, the liming recommendation for tropical pastures was a controversial subject due to doubts about the forage plants′ needs and due to the efficiency of liming without incorporation at depth (Oliveira *et al.*, 2003). However, currently with new knowledge about the path of nutrients at-depth, and with the adoption of mineral fertilization in intensive areas, liming has become a routine technique in pasture formation, recovery, and maintenance. Brazil has around 112 million ha of cultivated pastures. Thus, the scaling up to livestock farms is possible.

5. Impact on soil organic carbon stocks

Table 130. Carbon stocks of a tropical Brazilian Oxisol under Signalgrass pasture affected by soil fertility management

Depth (cm)	Soil C stock (t/ha)				
	Natural vegetation	T00	T0f	T2f	T4wf
0-10	23.2±0.8	30.3 b	59.9 a	54.4 a	53.0 a
10-20	22.9±1.0	23.6 b	25.0 b	41.8 a	38.9 a
20-40	25.1±1.1	40.4 a	40.9 a	40.7 a	41.2 a
40-60	21.5±0.4	32.5 a	32.8 a	28.3 a	26.7 a
60-80	15.3±0.2	24.7 a	23.7 a	27.0 a	21.1 a
80-100	16.9±0.8	19.6 a	21.1 a	22.5 a	27.6 a
Total	129	174 to			223

Means followed by the same letter, in the same soil depth, are not different by Tukey test at 5% level. The signal ± indicates the standard deviation (SD)

The highest amount of carbon was observed in soil samples under pasture, mainly in treatments with the addition of mineral fertilizer (t0f, t2f, and T4wf, Table 130). The carbon difference is greater on the surface (0-10 cm) than on deeper soil horizons due to the high input and accumulation of plant biomass, and a higher activity of soil organic matter. There was a general trend of SOC exponentially decreasing with depth. The carbon content is lower in an area with natural vegetation due to the lower supply of biomass and higher mineralization rate. Signalgrass has a robust root system that spreads deep into the soil, and the above-ground biomass also generates a significant amount of residual straw resulting in SOC increases. The N input stimulated SOC accumulation on the top layer. The total carbon stocks (0-100 cm) in the natural vegetation system (reference site) was 129 t/ha, while the carbon stocks determined for pastures ranged from 174 to 223 t/ha. The amount of carbon stock values found in this case study is similar to that determined at the same depth by Fisher *et al.* (1994), also of approximately 200 t/ha, in the Colombian savannas and to that found by Corazza *et al.* (1999), 150 t/ha, in *Cerrado* pastures cultivated with Signalgrass. Considering the 27-years-old pasture, the accumulation rate of total carbon stocks ranged from 1.7 to 3.5 tC/ha/yr. Compared to the soil under the natural vegetation, liming, and mineral fertilizer application to the Signalgrass pasture for 27 years had promoted sequestration of 6.1 to 12.8 t CO_2 /ha/yr from the atmosphere.

6. Other benefits of the practice

6.1. Benefits of soil properties

Liming improves P, Ca, and Mg availability, increases CEC, reduces Al and Mn toxicity, and improves soil aggregation and structure. Overall, liming improves the soil's ability to provide essential nutrients, as well as the plants' ability to uptake water and nutrients by enriching root growth and increasing soil microbial activity. Moreover, increasing soil pH and exchangeable bases stimulate OM decomposition and mineralization by promoting microbial activity (Haynes and Naidu, 1998; Fageria and Baligar, 2008). The results of this study case showed that high N levels decreased the soil pH and base saturation, while liming raised both parameters. Liming was required, especially as a source of Ca and Mg for Signalgrass. There were no effects of higher doses of limestone on the dispersion of soil particles and soil compaction. Thus, soil structure was preserved, as well as the macropores and, consequently, the hydraulic permeability or soil water conductivity. The field saturated hydraulic conductivity varied between 0.6 and 1.4 m/h, in treatments with mineral fertilization and high forage production (Primavesi *et al.*, 2004).

6.2 Minimization of threats to soil functions

Table 131. Soil threats

Soil threats	
Soil erosion	Lime and fertilizer application improve pasture growth and soil cover, and reduce soil erosion (Rocha Junior *et al.*, 2017)
Nutrient imbalance and cycles	Liming enhances mineralization and nitrification of organic N, (Bolan *et al.*, 2008; Primavesi *et al.*, 2008).
Soil acidification	Liming improves low soil fertility as a limiting factor for crop production limed by adding calcium (Ca) and magnesium (Mg) to the soil, increasing pH, and neutralizing the exchangeable aluminum (Al) content (Yamada, 2005, Souza and Lobato, 2004).
Soil biodiversity loss	Soil acidity correction increases the microbial activity (Albuquerque *et al.* 2003; Bolan *et al.*, 2008)
Soil compaction	Liming improved water aggregate stability and soil organic matter in the 0-10 cm layer (Bonini and Alves, 2011).
Soil water management	

6.3 On production

Compared to a control treatment with only mineral fertilization, liming and application of mineral fertilizer in a Ferralsol under Signalgrass produced between 9.8 to 13.5 t/ha of dry matter (Primavesi *et al.*, 2004, 2008). In addition to increased yield, other advantages of higher aboveground biomass of improved pastures were observed, thereby reducing soil temperature and organic matter decomposition. Oliveira *et al.* (2003) showed that limestone increased Signalgrass root production.

6.4 Mitigation of and adaptation to climate change

Well-managed pastures can increase the carbon stocks of the soil. However, the amount of SOC accumulation by improved pasture will depend on local climate conditions (rainfall and temperature), soil properties (texture and mineralogy), management practices, and economic resources (Batlle-Bayer, Batjes and Bindraban, 2010; Jantalia *et al.*, 2007; Haynes and Naidu, 1998). Batlle-Bayer, Batjes and Bindraban (2010) reviewed different studies that indicated the potential of lime-fertilized *Urochloa* pastures to increase soil carbon stocks ranged from 41 to 69 tC/ha to 0.2-m depth, with accumulation rates ranging from 0.2 to 0.7 tC/ha/yr.

Scurlock and Hall (1998) highlighted that the sustainable approach consists of managing the existing pastures to optimize carbon storage instead of the replacement of native vegetation by improved pastures. The potential for reduction of GHGs emissions by the Brazilian livestock is remarkably high (Bustamante *et al.*, 2012), and it should be accompanied by reduction of deforestation, secondary forest regeneration, enteric fermentation reduction, pasture restoration, and elimination of fire in pasture management. Pasture restoration is one of the leading strategies of the Brazilian governmental program “Low-Carbon Agriculture” to reduce or compensate the carbon emissions (Sá *et al.*, 2017). Productivity gains in livestock have been pointed out as a promising alternative to achieve climate change mitigation together with economic growth (Silva *et al.*, 2016; Silva, Ruviaro and Ferreira Filho, 2017); Oliveira *et al.* (2017) showed that pasture intensification lead to a reduction in GHG emissions, considering emissions per unit of production increase, and beyond that, an increase in soil carbon storage was achieved.

6.5 Socio-economic benefits

Table 132 shows that soil acidity control by liming also provides economic benefits. Based on Oliveira *et al.* (2003), forage yields were higher in pastures that received (i) only liming and (ii) liming and fertilization than in pastures that received (iii) no input or (iv) only fertilization. Considering dry matter yield results, the animal stoking values, and weight gains were estimated. Additionally, the efficiency was calculated considering the market price of meat and limestone, and the cost of liming operation. The economic advantage of liming was highlighted considering that for every US dollar invested in liming it has led to a return on beef production of up to US$2.20 using limestone only and up to US$3.50 combining limestone and fertilizer.

Table 132. Simulation of animal stocking, carcass gains, and economic return for limestone and fertilizer use in beef cattle pastures

	Degraded Pasture	Limed Pasture	Fertilized Pasture	Limed and Fertilized Pasture[€]	Average without liming	Average with liming
Dry matter yield (kg/ha)	4,4	5,9	16,4	19,0	14,4	16,8
Stocking (AU/ha)[&]	0,9	1,3	3,5	4,1	3,1	3,6
Weight gain (kg/ha)[†]	231,6	315,0	869,0	1010,3	762,8	894,5
Carcass yield (@/ha)[£]	7,7	10,5	29,0	33,7	25,4	29,8
Economic return[§]	-	2,2	-	-	-	3,5

Assumptions: Grazing efficiency = 70%; Dry season = 180 days; wet season = 185 days

[€] Liming = 1.5 t ha^{-1}; Fertilizer = 100 kg ha^{-1} N; P = 15 ppm, and K_2O = 3%

[&] AU = Animal unit = 450 kg

[†] System starts with young male cattle (300kg) to be finished. Daily dry matter consumption = 2% of living weight. Daily weight gain: dry season = 0.25 kg per day, wet season = 0.7 kg per day

[£] Carcass yield = 50% efficiency, 1 @ = 30 kg living weight.

[§] (@ Yield with lime – @ Yield without lime) $(\text{liming costs})^{-1}$. Prices: @ = US\$45.00; lime = US\$29.40 per ton; liming operation = 0.5 h X US\$25.50 per h. US\$ 1.00 = R\$5.10

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 133. Soil threats

Soil threats	
Nutrient imbalance and cycles	High doses of N fertilizer with low liming can result in losses of nitrate to the subsoil, with Ca and N-NO3 binding, leading to acidification of the surface layer, with consequent loss of N-NO3 and K (Primavesi *et al.*, 2008).
Soil salinization and alkalinization	Surface application of high lime rates promoted chemical stratification resulting in dramatic increases in topsoil pH and exchangeable Ca and Mg levels with minimal mitigation of subsurface soil acidity in croplands no-till areas (Nunes *et al.*, 2019).

Soil threats	
Soil erosion	Excessive increased in soil pH values were related to increased clay dispersion, destroyed soil aggregates, and reduced infiltration of Oxisols (Haynes and Naidu, 1998; Costa *et al.*, 2004; Hunke *et al.*, 2015).
Soil compaction	
Soil water management	

7.2 Increases in greenhouse gas emissions

An estimate of the net GHG balance (soil C sequestration minus emissions of nitrous oxide and methane) made by Oliveira *et al.* (2017) is presented in Table 134. Intensive systems demand more nutrient inputs (fertilizer and lime), and lead to an increase in animal stocking rates, increasing the total emissions. However, there is also a greater increase in C storage in the soil leading to a final balance for this system is more positive.

Table 134. The balance between GHG emissions and removals, considering two beef cattle production systems

Pasture management	Animal stocking	Soil C rate [†]	C storage[£]	CH_4 animal[€]	N_2O soil[§]	CH_4 soil[€]	CO_2 Limestone[&]	Total emissions	Net difference
	n per ha	t/ha/yr	t CO_2eq/ha/yr						
Extensive	2.04	1.7	6.24	2.95	0.00203	0.00068	-	2.9527	3.29
Intensive	3.13	3.13	11.49	5.55	0.00068	0.00068	0.47	6.0214	5.4686

Source: Adapted from Oliveira et al. (2017)

[†] Results for the 0-1.0 m depth

[£] Conversion factor = 3.67

[€] Emission metrics for CO2 -equivalent emissions (100-year GWP): 28 (IPCC, 2014)

[§] Emission metrics for CO2 -equivalent emissions (100-year GWP): 265 (IPCC, 2014)

[&] 0.13 t C-CO2 per t of limestone, with 50% emission (De Klein *et al.*, 2006). Limestone doses = 2 t/ha

7.3 Conflict with other practice(s)

Liming recommendation for pastures was a controversial subject due to doubts about the response of tropical pastures. However, with new knowledge about the detailed path of nutrients and the adoption of mineral fertilization in intensive areas, new concepts have been created, and liming has become a routine technique both in the formation and maintenance or restoration of pasture areas, having a relevant role in the efficiency and sustainability of pasture (Cantarella *et al.*, 2002; Martha Jr. and Vilela, 2002; Primavesi *et al.*, 2008).

Soil plowing and disc-harrowing to incorporate limestone in soils cultivated with pastures was also a controversial practice. The slight increase in forage production observed when the limestone was incorporated into the soil (Primavesi *et al.*, 2004) did not compensate for the high-cost machine operation (Caires, Banzatto and Fonseca, 2000). Oliveira *et al.* (2003) observed that disc harrowing harmed the forage root system development and caused a decrease in the soil carbon levels. Primavesi *et al.* (2008) stated that the adequate amounts of limestone applied consists of reaching optimum level of soil base saturation needed for forage growth (35 percent to 40 percent) with complimentary annual surface broadcast to control soil acidity caused by mineral nitrogen fertilizer used.

8. Recommendations before implementing the practice

The soil chemical analysis is essential for the liming and fertilization recommendation, aiming for economically viable and environmentally correct livestock production (Cantarella *et al.*, 2002). Guidelines for liming and fertilizer application are essential tools to integrate and transfer the results of research on soil fertility and plant nutrition to farmers (Cantarella, Raij and Quaggio, 1998). The first and most critical step of the chemical analysis concerns the soil sampling process, and then the analysis carried out in a high-quality soil analysis laboratory (Bernardi *et al.*, 2002; Souza and Lobato, 2004).

9. Potential barriers to adoption

Table 135. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	CO_2 emissions from lime are GHG sources (Mazzetto *et al.*, 2015).
Cultural	Yes	Many times, the extensive managed pastures do not receive nutrients input or receive amounts below plant's needs (Cantarella *et al.*, 2002) based on a wrong concept of tropical grasses are rustic and can produce anyway.

Barrier	YES/NO	
Social	Yes	Low-productive livestock farms do not invest in pasture maintenance and amelioration (Cantarella *et al.*, 2002; Martha Jr. and Vilela, 2002) due knowledgement lack of how adequately managed productive pasture.
Economic	No	Liming is the most common way to control soil acidity in Brazil due to its favorable cost-benefit and positive effects on fertilizer efficiency (Cantarella *et al.*, 2002; Yamada, 2005; Fageria and Baligar, 2008).
Institutional	No	Soil testing facilities are spread in all agricultural regions, and liming recommendations are well-known and adopted for many crops (Cantarella, Raij and Quaggio, 1998; Bernardi *et al.*, 2002; Souza and Lobato, 2004).
Knowledge	No	Several experimental results show the positive effects of liming acidic soils, and there are established efficient recommendations (Fageria and Baligar, 2008).
Natural resource	No	In Brazil, there is many carbonate rocks with potential for agricultural use and production occurs close to agricultural regions (Nahass and Severino, 2003).

Photo

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Photo 63. Experimental plots of Signalgrass pasture: control (T00) on left and limed and fertilized (T4wf) on right

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33. Conservation agriculture in lowlands – an experience from South America

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1. Practice(s) used

Conservation agriculture, Integrated crop-livestock systems, Wetland management

2. Description of the case study

The reduction or elimination of excess soil moisture is one of the most important steps to overcome obstacles to conservation agriculture (CA) in hydromorphic soils of lowlands. Raised-beds and ridge-and-furrow are two well-known techniques of cultivation in lowland fields, constituting efficient ways to protect crops from the excess of water in the soil. However, these methods commonly require intensive soil preparation and are hardly compatible with CA practices, like no-tillage. The challenge to establish a system conducted entirely under conservation agriculture in a lowland paddy still has not been totally solved in many regions worldwide. By considering efficient soil drainage[6] as a must-have to enable crop diversification in lowlands and conservation agriculture as the way to increase soil quality in the long term, this case study presents an alternative concept to the commonly used ridges. In this new concept, instead of the temporary, narrow ridge design (up to 1 m width, for instance) that last only for a few cropping seasons, almost permanent wide (8 m width) ridges were built (Figure 33 and Photo 64) and cultivated strictly under the principles of conservation agriculture combined with crop-livestock integration (agropastoralism). Grain crops like soybean (*Glycine max*) and maize (*Zea mays*) (one crop per season) were cultivated during summer, and pastures (ryegrass (*Lolium spp.*) and black oats) with beef-cattle occupied the field during winter. The new concept was evaluated and validated in a 9-year study at the Lowlands Experimental Station of Embrapa Clima Temperado, in south Brazil (31.8134 S; 52.4736 W).

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[6] An efficient soil drainage means, firstly, the field will drain fast (e.g. after a rainfall event) and uniformly (the entire field is drained, not leaving poorly drained patches which take a long time to dry, damaging crops). Secondly, it means that the field has well-located channels that allow avoiding damage caused by seasonal or temporary flooding and keeping water table below the root zone.

3. Context of the case study

Rice (*Oryza spp.*) is the main staple-food in Brazil. Around 80 percent of the cereal is produced in the lowlands of the southern part of the country. The crop is fully irrigated, the average grain yield being near eight tons per hectare in cropping season 2020 (IBGE, 2020). The climate of most part of the region is humid subtropical (Cfa), with an annual average temperature near 18 °C and annual precipitation around 1400 mm. Soil characteristics like poor drainage, susceptibility to compaction, acidity and low levels of organic matter have restricted the cultivation of crops other than rice. Planosols predominate in these areas (Santos *et al.*, 2018), which are characterized by a low-to-medium level of fertility. Soil organic matter is classified as "low" (<2,5 percent) for 71 percent of the arable lowland in this region (Boeni *et al.*, 2010). The study described hereby was conducted in a Haplic planosol at 13 meter above sea level, in a soil with bulk density of 1.49 kg/dm^3, 20 percent of clay, 38 percent of silt, 42 percent of sand and 1.5 percent of organic matter.

In general, large improvements in the rice-based cropping systems in south Brazil occurred in the last decades. However, new drivers have become significant in the regional context, of which are especially relevant the need to increase soil quality and the expansion of soybean over the arable lowlands. Differently from rice, soybean and other species require an efficient drainage system to succeed. In order to form a favorable environment for rainfed crops and to create conditions to apply practices associated with conservation agriculture, we identified that building large ridges (in our study, with 8 m width as depicted in Figure 33) would be a cost-effective approach. This method efficiently keeps the soil dry, thereby reducing machinery-associated soil compaction (common in wet soils) and protecting summer cash-crops from waterlogging. In addition, the combined effect of the adoption of no-tillage with the excellent drainage provided by the ridges allowed to extend the growing season for the early winter, time on which pastures were cultivated. The dry biomass produced in winter reached 4.5 t/ha in the novel system, contrasted with around 1 t/ha produced in other traditional rice-based models. Production of biomass was important to increase soil organic matter. More details and results of this work can be assessed in Theisen *et al.* (2017).

4. Possibility of scaling up

The concept of using large-based ridges as a drainage system can be adapted and used in lowlands worldwide. Because of the inherent simplicity of its construction (Photo 64), farmers at different technological levels can build a system. Our long-term evaluations were conducted in areas from 2 to 19 ha in south Brazil (Photo 65 and Photo 66). In other regions that share similar soil and climate, it is possible to build and adapt not only the physical structure of the ridges, but also a similar scheme of crop rotation, including practices related to conservation agriculture. Farmers in central Brazil have adopted the system in a larger scale (e.g. fields of ~ 1000 ha) with 20m-width ridges. In that case, tropical pastures are being produced, in originally flat areas until then underused due to seasonal flooding.

5. Impact on soil organic carbon stocks

Table 136. Impact on soil organic carbon stocks

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Reference
Brazil (southern region)	Humid subtropical (Cfa*)	Haplic planosol	27.4	0.77	9	Theisen (2017)

*According to Köppen's climate classification

6. Other benefits of the practice

6.1. Improvement of soil properties

Cash crops (soybean and maize) were fertilized with N, P and K following the regional recommendation and soil analysis. Pastures were fertilized with N, at varying rates from 25 kg to 50 kgN/ha per cropping season. We observed an increase in soil K and P levels, from 50 to 80 and 2.4 to 85 mg/dm^3 from 2006 to 2015 for K and P, respectively. Soil physical or biological properties were not evaluated.

6.2 Minimization of threats to soil functions

Table 137. Soil threats

Soil threats	
Nutrient imbalance and cycles	Cover crops and crop-livestock integration conducted in large ridges potentially improve nutrient balance and cycling (Theisen *et al.*, 2017).
Soil biodiversity loss	Practices of conservation agriculture (mulching, minimum soil disturbance) potentially increase soil biodiversity (Finn *et al.*, 2017).
Soil compaction	Large ridges keep the soil dry, which reduces the intensity of traffic-induced soil compaction (Ahmadi and Ghaur, 2015); roots of pasture grasses and cover crops can also help to reduce soil compaction (Ralisch *et al.*, 2010).
Soil water management	Mulching helps preserving soil moisture for crops in dry seasons (Gan *et al.*, 2013).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Official data (IBGE, 2020) about the grain yield of maize and soybean was collected from 14 nearest municipalities around the experimental station for each cropping season during the timespan of the experiment (2006-2015). Compared with these regional averages, the ridge-based production system significantly increased grain yields of maize (+274 percent) and soybean (+19 percent). In a similar way, reducing the restrictions caused by poor drainage allowed production of high-quality pastures during the winter, resulting in 4.5 times higher biomass production. Hence, besides grain production, livestock (either for milk or for meat) can be favored in the paddies conducted with large ridges. The method, in synthesis, is an efficient way to intensify and diversify agricultural production in hydromorphic, hard-to-work, flat soils.

6.4 Mitigation of and adaptation to climate change

One of the main principles of conservation agriculture is the maintenance of a layer of straw on the soil surface. Mulch, along with other practices, like minimal or zero soil disturbance, creates favorable environment to increase soil organic carbon. Both factors (the mulch layer and high organic matter content) potentially increase the resilience of the cropping system against drought and other extreme climatic events. Evaporation of water from the soil is reduced by the mulching layer, whilst organic carbon increases the capacity of soils to retain water. Along with the contribution related to water balance, increasing soil organic matter also have a well-known and significant role in the soil-atmosphere carbon balance, a factor connected to global warming.

6.5 Socio-economic benefits

The large-ridges system proved to be an interesting approach to enable the cultivation of a larger variety of species (grains, pastures and cover crops) in a once very wet and easily floodable paddy, originally limited to irrigated rice and livestock production. Projecting the context to a farm level, the diversification infers more sources of income throughout a year, which can increase the monetary autonomy and self-sufficiency of farmers. This is an important point, especially for those limited in financial resources. In our long-term study we compared some financial-related indicators across five distinct lowland cropping systems, one of which is the reported model herein. Monetary risk (overall costs), net returns and profitability were all better in the large-ridges system with crop-livestock integration model than in the other cropping systems. Details about the cropping systems, methodology and values can be accessed in Theisen (2017).

7. Potential drawbacks to the practice

7.1 Increases in greenhouse gas emissions

In the long-term study here reported all inputs, outputs, energy, machinery used, the time required for each operation in the field, the biomass produced per crop and cropping season as well as soil organic matter levels at the beginning and at the end of the experiment were measured and computed. A synthesis of GHG emissions and balance for the ridge-based cropping system, after its consolidation, normalized to CO_2-eq is summarized as: emitted CO_2-eq was 2.64 (+/- 0.30) t/ha/yr; CO_2eq balance was 0.19 (+/- 0.30) t/ha/yr. Details, comparison with other cropping systems and other related indicators are available in Theisen (2017).

7.3 Conflict with other practice(s)

A field maintained with large-base ridges will remain well drained, since the shape of the ridges does not allow the water to accumulate in the soil surface. This condition undoubtedly is not the best suitable to grow surface-irrigated rice, once this method of irrigation requires a flat soil to succeed. For this reason, we indicate the ridge-based method for exceeding lowlands not cultivated with rice, or for areas where irrigated rice is part of a long-term rotation (three or more years, for example).

7.4 Decreases in production (Food/fuel/feed/timber/fibre

Nothing meaningful was verified in terms of negative impact. Indeed, the large-base ridges promoted positive impacts on the production of crops, pastures and cover crops.

8. Recommendations before implementing the practice

The ridges can be constructed by directing the ploughing equipment to form the desired shapes in the field (Figure 33-A) or by adjusting the equipment that is already used in soil levelling, like a soil planer (Figure 33-B). The central ridge depicted in Figure 33-A illustrates the basic formation of a ridge after the first pass of a moldboard plow; to eliminate soil clods and form a smoother and more uniform shape (like the lateral ridges in Figure 33-A), a subsequent operation with a light disk harrow may be needed. The ridges can present variable width, height and length, and a good practice is to build them in a size that matches with a multiple of the distance of machinery wheels, or, for example, twice the width of the cutter bar of a combine harvester. An important aspect in this technique is that the relatively large width of ridges permits common management practices (e.g. seeding, harvesting, pest control) be performed using the same machinery as in upland fields.

9. Potential barriers for adoption

Table 138. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Farmers used to work exclusively with irrigated rice in lowlands can find difficulties to manage rainfed crops or livestock.
Economic	No	The cost of building the ridges is similar to conventional soil preparation (plough + arrow). The difference is that once built, the ridges can last for several years (10 or even more).
Institutional	Yes	The proper functioning of institutions, particularly the rural extension services, increase the chance of adoption of this method by farmers. From this point of view, lack of institutional resources is a potential barrier for adoption of system, mainly for farmers highly dependent on these services as source of knowledge and improvements in their practices (as well pointed by Navarro, 2020).
Knowledge	Yes	The practice of conservation agriculture requires a minimum level of familiarity with mulching, minimal soil disturbance and crop rotation. Not all farmers or assistants have the knowledge required. In the same way, not all farmers can efficiently manage crop-livestock integration. From this perspective, knowledge can be a barrier to the successful adoption of the system.

Visual representations of the practice

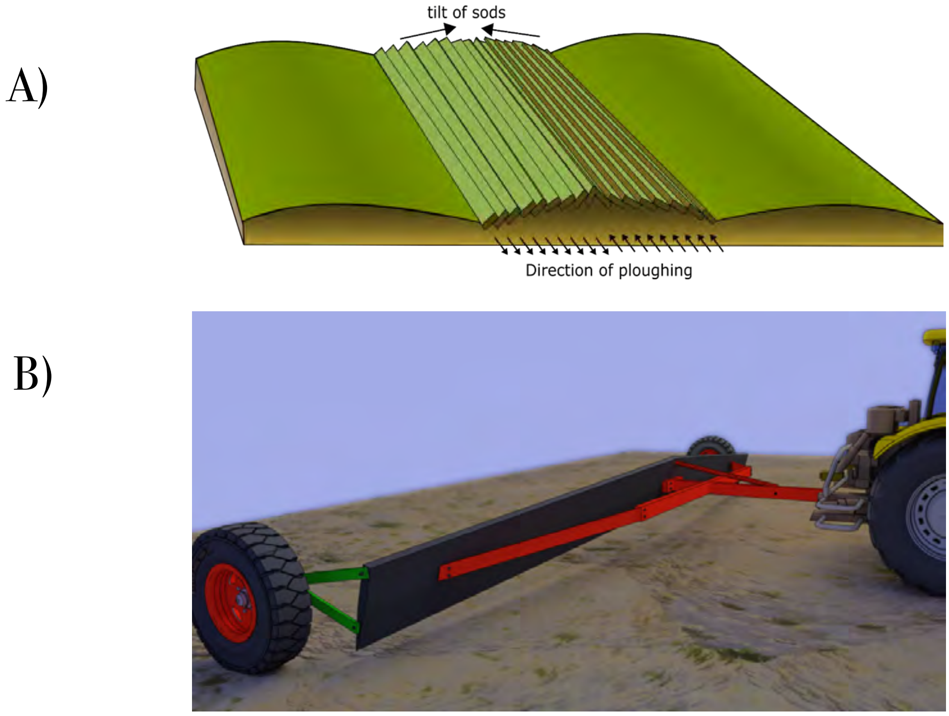

Figure 33. Large-based ridges can be built by adjusting the direction of ploughing

With a common moldboard or disk-plow (a), or with equipment like blade-based land planes (b). Fig. 1-a was drawn based on https://en.wikipedia.org/wiki/Ridge_and_furrow; Fig. 1-b was produced by the authors.

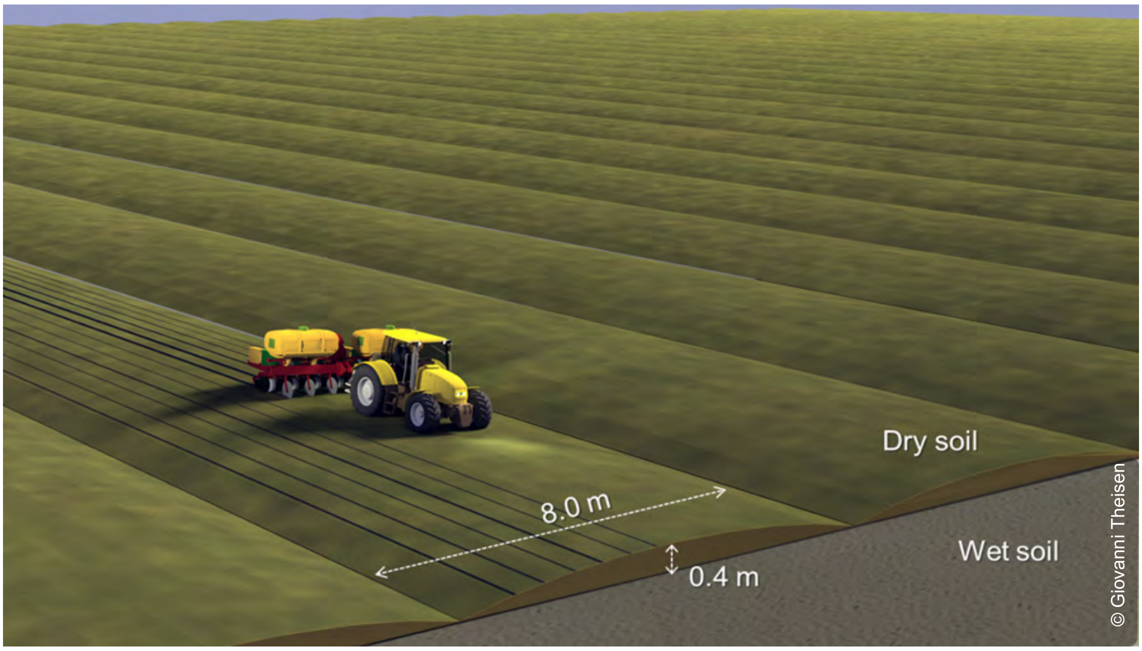

Photo 64. Simplified illustration of a field where large ridges were built

Photo 65. Soybean growing in large ridges in lowlands. Pelotas, RS, Brazil, January 2013

Photo 66. Pasture of black oat (Avena strigosa) cultivated in 8-m large ridges in a plot of 19 ha. Pelotas, Brazil, August 2012. (with permission of participants)

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34. Integrated farming in tropical agroecosystems of Brazil

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1. Related practices and hot-spot

Integrated crop-livestock systems, Silvopastoralism, Agrosilvopastoralism, Restoration of degraded grassland; Grassland

2. Description of the case study

Integrated systems are an agriculture practice that combines crop, livestock, and forestry activities in the same area. These systems may be categorized into: (1) integration of crop–livestock (agropastoral system, ICL), (2) crop–forestry (silvoarable system, ICF), (3) livestock–forestry (silvopastoral system, ILF) and (4) crop–livestock–forestry (agrosilvopastoral system, ICLF). The choice of which to use will depend on the economical and geographical characteristics of the region, access to financial incentives, farming facilities, the skills of farmers, production strategy and cultural aspects (Balbino, Cordeiro and Martínez, 2011a; Balbino *et al.,* 2011b; Galford, Soares-Filho and Cerri, 2013; Gil, Siebold and Berger, 2015).

Integrated systems are one of the promising practices for pasture restoration (Muniz *et al.,* 2011; Assis *et al.* 2015; Loss *et al.,* 2011) and to reduce the effects of land mismanagement such as on loss of soil C and net GHG emissions (Lemaire *et al.,* 2014). Integrated systems also favour the efficient use of inputs due to synergistic interaction of the different land use types in the same area (Vilela, Martha Junior and Marchão, 2012; Peyraud, Taboada and Delaby, 2014; Soussana and Lemaire, 2014).

3. Context of the case study

The data presented here is relevant for integrated systems under tropical climate (southern Amazon and *Cerrado*, the neotropical savannah of Brazil). These regions typically have dry winter (May–August to May-October), and the average annual rainfall ranges from 1 500 to 2 000 mm, of which about 95 percent is concentrated between September and April. The mean annual temperature varies from 23 to 26 °C. The soils are predominantly Ferralsols (FAO, 2015). Climate is a key factor for a rapid soil organic matter turnover.

4. Possibility of scaling up

The level of adoption of integrated systems in Brazil, including all biomes, was around 1.87 million ha in 2005 (Balbino, Barcellos and Stone, 2011c) and reached 11.47 million ha in 2015 (Embrapa, 2016). On a national level, the largest growth occurred among livestock farmers (meat and dairy) in the last 5 years, which was 10 percent, while grain (soybean and corn) producers adopted the system at 1 percent rate every 5 years (Embrapa, 2016). However, important differences exist among regions in the country. While the increase in the adoption of integrated systems in the last 5 years was reasonable, dedicated attention has to be given to maintaining the adoption trend. One of the main reasons for adoption among ranchers was the pressure to reduce the environmental impact of production and restore degraded pastures, which are two interlinked objectives. Among the grain producers, the primary driver was increasing yields (Embrapa, 2016). On a regional level, access to information, education, culture, supply chain infrastructure and historical land use patterns (Gil, Garrett and Berger, 2016) are determinant for the successful adoption of ICLF.

A great diversity of integrated systems exists worldwide, evidencing the need for and adaptability of the concept to various eco-regions and production purposes (Sulc and Franzluebbers, 2014; Bell, Moore and Kirkegaard, 2014; Peyraud, Taboada and Delaby, 2014). These are common in being able to capture ecological interactions between different land use systems, providing opportunities for more efficient agroecosystems in nutrient cycling, protection of the natural habitats, soil quality improvement and biodiversity (Lemaire *et al.,* 2014).

5. Impact on soil organic carbon stocks

Most literature on integrated systems where both crops and livestock are included show results from ICL systems that lack the presence of the forestry component. Accumulation rates in three different farms (two in the Amazon and one in the Cerrado (neotropical savannah of Brazil) biome) ranged from 0.82 to 2.58 t C/ha/year (3.00-9.46 t CO_2/ha/year) at 0.0-0.3 m soil depth, 1–8 years after the conversion of continuous annual crop systems into ICL (Carvalho *et al.,* 2010). In an ICLF system of the southern Amazon, accumulation was 1.47 t C/ha/year (5.39 t CO_2/ha/year) at 0-1 m soil depth compared to an adjacent degraded pasture (Oliveira *et al.,* 2018). Most of the stored C was found under the tree lines below 0.3 m. In southeast Brazil, Bieluczyk *et al.* (2020) measured a gain of 1.96 and 1.74 t C/ha/year (7.19 and 6.38 t CO_2/ha/year) in ICL and ICLF respectively, at the top 0.4 m soil layer, compared to extensive grazing. The inclusion of trees in ICL, however, did not further increase C stocks but reduced it at 0.22 t C/ha/yr. It was probably due to the reduction of C and N inputs to the soil caused by limited growth of annual crop and grass species under tree shades. Adequate management of ICLF (e.g. distance between trees, nutrient balance, especially N) is a key to achieve effective soil C accumulation (Table 139).

Table 139. Changes in soil organic carbon stores reported for integrated systems, Brazil

Location	Climate zone	Soil type (FAO, 2015)	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Brazil, South-East, Tropical Savannah	Humid Tropical	Oxisol	-	1.96	6	0-40	ICL, MAP 1545 mm, MAT 20.6°C, 40 › Clay% › 30	Bieluczyk *et al.* (2020)
			-	1.74			ICLF, MAP 1545 mm, MAT 20.6°C, 40 › Clay% › 30	
Brazil, South Amazon		Rhodic Kandiudox	50.10	2.85	4	0-30	ICL, MAP 2200 mm, MAT 26°C, 70 › Clay% › 60, highly fertile soil	Carvalho *et al.* (2010)
		Typical Hapludox	57.40	1.35			ICL, MAP 2000 mm, MAT 28°C, 60 › Clay% › 50	
Brazil, Central-West, Tropical Savannah		Typical Hapludox	66.44	0.82	8	0-30	ICL, MAP 1500-1800 mm, MAT 23°C, 70 › Clay% › 60	
Brazil, South Amazon		Oxisol	110.66	1.47	12	0-100	ICLF with 3 rows of eucalyptus by tree line, nutritionally balanced soil, MAP 1954 mm, MAT 26°C, 0-30 cm 60 › Clay% › 50, 30-100 cm 70 › Clay% › 60	Oliveira *et al.* (2018)
			55.05	0.58		0-30		
			55.61	0.89		30-100		
			110.66	-0.04		0-100	ICLF with 3 rows of eucalyptus by tree line, N-deficient soil, MAP 1954 mm, MAT 26°C, 0-30 cm 60 › Clay% › 50, 30-100 cm 70 › Clay% › 60	
			55.05	0.01		0-30		
			55.61	-0.05		30-100		

MAP: Mean Annual Precipitation; MAT: Mean Annual Temperature

6. Other benefits of the practice

6.1. Improvement of soil properties

Because of the synergistic interaction of the different land use types in the same area (Vilela, Martha Junior and Marchão, 2012; Peyraud, Taboada and Delaby, 2014; Soussana and Lemaire, 2014) integrated systems improve biophysical properties of soils such as microbial biomass C, soil organic matter, pH, soil structure, water holding capacity, microbial diversity (Muniz *et al.,* 2011; Assis *et al.,* 2015; Loss *et al.,* 2011; Lisboa *et al.,* 2014), as well as nutrient cycle.

6.2 Minimization of threats to soil functions

Table 140. Soil threats

Soil threats	
Soil erosion	Quality pasture and trees increase soil cover. Improved soil properties reduce susceptibility to soil loss.
Nutrient imbalance and cycles	Enhanced nutrient cycles and reduced dependence on external inputs.
Soil contamination / pollution	Diffuse manure spreading increases SOM and potentially fosters soil buffer capacity to metals availability.
Soil acidification	Increased SOM helps to diminish Al toxicity to crop plants.
Soil biodiversity loss	Increased aboveground diversity, which is an important driver of soil microbial community response, enhances belowground biodiversity and affects microbial structure.
Soil compaction	Rotation of land use, reduced tillage, crop rotation with dual purpose forage grasses.
Soil water management	Better water cycles balance and water regime due to improved soil aggregation and aggregate stability in C and N rich soils.

6.3 Increases in production (e.g. food/fuel/feed/timber)

This multi-functional system provides biomass for feed, food, energy (as firewood and charcoal), fiber and other non-food products such as timber, cellulose, furniture and construction materials.

6.4 Mitigation of and adaptation to climate change

In future scenarios under climate change, agrosilvopastoral systems represent an efficient mitigation and adaptation strategy, because they sequester C in the soil and especially when trees are included. Trees represent an additional CO_2 removal capacity from the atmosphere and enable the system to compensate at least partially the equivalent GHGs emitted from livestock (Alves *et al.,* 2015). However, appropriate management of ICLF (e.g. distance between trees, and nutrient balance, especially N) is vital to achieve effective soil C storage. Also, soil surface covered by plant residues and grasses helps the production system adapt to dry spells in the rainy season (uncharacteristic shortage of precipitation during a period within the rainy season, likely result of climate change) and soil water loss in general.

6.5 Socio-economic benefits

Besides the biophysical synergistic effects, integrated systems provide opportunity for better use of machinery, higher farmers' income, and more jobs in rural areas (Macedo, 2009; Vilela, Martha Junior and Marchão, 2012). These systems also enhance resilience against biophysical and economic stresses compared to highly specialized cropping or pastureland use (HLPE, 2016).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 141. Soil threats

Soil threats	
Nutrient imbalance and cycles	If nutrient balance is not achieved, soil C accumulation may be hampered.
Soil contamination / pollution	Potentially reduced external inputs.
Soil compaction	While rotation of land use, reduced or zero-tillage, crop rotation with dual purpose forage grasses potentially reduce soil compaction, livestock stocking rate should be controlled in order not to offset the positive effect of soil management.

7.2 Increases in greenhouse gas emissions

With the implementation of integrated systems, production intensity is likely to increase, which means larger number of animal units per ha. Consequently, N_2O (urine, dung, and eventual mineral N) and CH_4 (enteric fermentation) emissions are expected to increase. On the other hand, the improved pasture and the trees increase SOC density and contribute to atmospheric CO_2 removal. It was estimated that the increase of land area under ICLF in Brazil between 2010 and 2016 contributed to the mitigation (removal) of around 3.79 Mg CO_2eq/ha/yr (Manzatto *et al.*, 2020).

7.3 Conflict with other practice(s) and tools to overcome barriers

The complexity of integrated systems, as opposed to highly specialized production systems, may hamper their large-scale adoption. Carbon credit benefits through introducing certification systems seem to be an important incentive, in which the producer could get significant economic gains by implementing the integrated systems (Oliveira *et al.,* 2008; Fernandes and Finco, 2014; Paul *et al.,* 2013).

7.4 Decreases in production (Food/fuel/feed/timber/fibre

Well-managed integrated systems tend to have an overall positive impact on productivity.

7.5 Other conflicts

Because of the complexity of integrated systems, technical support is imperative, particularly for small- and medium-scale farmers, as well as sound complementary policies and good governance so that a "rebound effect" does not lead to increased deforestation and other adverse social and environmental impacts (Martha Júnior, Alves and Contini, 2011; Latawiec *et al.,* 2014). Public extension services, in collaboration with the private sector that strengthens information flow and enables investment in infrastructure, are crucial to the success of integrated systems.

8. Recommendations before implementing the practice

As integrated systems combine activities from different areas of agriculture, it is important to seek technical assistance, and identify a best model for the farm to fulfil its objectives. This should include favourable soil and climatic conditions, available resources, infrastructure and personnel and their training needs, as well as marketing opportunities. A gradual implementation is always recommended, not exceeding 20 percent of the total planned area at a time. It is important to make a technical design and an economic plan. After implementation, continuous monitoring and analysis are necessary in order to make adjustments or corrections.

9. Potential barriers for adoption

Lack of knowledge and technical supports to small- and medium-scale farmers, as well as sound policies and good governance for implementation is a major drawback in accepting the systems. This includes inappropriate collaboration between public extension services and private sectors resulting in less information flow and investment in infrastructure.

Table 142. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Resistance to change.
Social	Yes	Rural areas abandonment.
Economic	Yes	Implementation cost, still not established certification scheme, poor infrastructure, market possibilities.
Institutional	Yes	Not enough technical support.
Legal	No	Heavy legal constraints to forest management.
Knowledge	Yes	More research is needed related to integrated systems management, especially ICLF (rotation, spatio-temporal arrangement, nutrient cycling, regionality etc).
Natural resource	No	Climate change impacts on precipitation.
Other	Yes/No	Enforcement and stability of public policies in the support of sustainable agriculture.

Photos


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Photo 67. Agrosilvopastoral system in Nova Canaã do Norte, Mato Grosso State, Brazil, refering to Oliveira *et al.* 2018

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35. Integrated crop-livestock systems on SOC sequestration in subtropical Brazil

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1. Related practices

Integrated crop-livestock systems

2. Description of the case study

The integrated crop-livestock system (ICLs) consists of a diversified agricultural, livestock and/or forestry production within the same area, simultaneously or in rotation/succession, and aims to achieve social, economic and environmental sustainability (Carvalho *et al.*, 2010; Moraes *et al.*, 2014a). Here we present a literature review on soil organic carbon (SOC) stocks and sequestration in subtropical Brazil. This region lies in the southern part of the country, in a climate zone with distinct seasons (Cfa or Cfb, Köppen) that allows the establishment of ICLs of cash crops for grain production in the warm-season and annual cover crops for grazing in the cool-season, both under no-tillage system (Carvalho *et al.*, 2010). Some areas also have integration with forest plantations (Dominschek *et al.*, 2018; Pontes *et al.*, 2018). Adoption of ICLs has been increasing in the last decades, but only few studies regarding SOC sequestration have been published yet. Benefits of ICLs include: SOC accumulation, improvement in soil physical properties, increase in nutrient cycling and crop productivity, and greenhouse gases (GHG) mitigation (Carvalho *et al.*, 2010; Assmann *et al.*, 2017b; Piva *et al.*, 2019; Ribeiro *et al.*, 2020b). These benefits are attributed to the livestock component during the cool-season grazing phase, which acts as a catalyst in many biogeochemical processes. However, those benefits depend greatly on the cool-season cover crops management, such as grazing intensity/stocking rate and nitrogen fertilization, factors that directly influence the amount of residue and nutrients added/returned to soil (Assmann *et al.*, 2017b; Cecagno *et al.*, 2018; Ribeiro *et al.*, 2020b).

3. Context of the case study

The subtropical Brazil comprises the southern states of Paraná, Santa Catarina and Rio Grande do Sul and covers an area of approximately 576 410 km^2, situated between latitudes 22° and 33° S. Most of the region (70%) has humid subtropical climate with hot summer (Cfa), where mean annual precipitation range is 700-3500 mm and mean annual temperature range is 15-24 °C (Alvares *et al.*, 2013). The remaining of the area has a humid subtropical climate with temperate summer (Cfb), with mean annual precipitation range of 800-3200 mm and mean annual temperature range of 12-22 °C (Alvares *et al.*, 2013). The geological composition of the region is predominantly magmatic and sedimentary rocks (GeoSGB, 2021) and most of soils are classified as Cambisols, Ferralsols, Acrisols and Nitosols (Embrapa, 2016b). According to IBGE (2019), the territory is used for agriculture (34%), livestock (33%), forest preservation (21%) and forest cultivation (8%).

The most common ICLs scheme adopted by farmers in subtropical Brazil is seasonally organized in a way that cash grain-crops like soybean, maize or rice are grown in the warm-season and annual cover crops like oats and ryegrass or dual-purpose wheat are grown in the cool-season for grazing. Grazing of cover crops is also an alternative for areas commonly left fallow in the cool-season, thereby increasing the land use intensification and income diversification for producers (Carvalho *et al.*, 2010; Anghinoni *et al.*, 2018). The ICLs are considered a win-win land use system, coupling economic gains with environmental protection. It is a system in which part of the fertilizer applied in summer crop is used also by grazed winter cover crops, reducing costs of establishment of grazed cover crops (Bernardon *et al.*, 2020) and where the animal excreta positively affects the nutrient cycling and thus nutrient availability to the following summer crops (Assmann *et al.*, 2015; Assmann *et al.*, 2017b).

4. Possibility of scaling up

The area of ICLs has increased considerably in the last two decades and currently occupies 13% of the agricultural land in southern Brazil (Embrapa, 2016a). According to Moraes *et al.* (2014a), 9 million hectares that are used for soybean, maize and bean cultivation can also be used with grazed cover crops in the off-season. Lowland areas that cover approximately 5 million hectares in Rio Grande do Sul state also have a significant potential to be used for ICLs (Moraes *et al.*, 2014a). Also, areas of degraded pasture can also be converted into ICLs, so that the management for soil amelioration in the crop phase, like lime and fertilizer application, positively affects the recovery of the grazed cover crop phase (Anghinoni *et al.*, 2013; Moraes *et al.*, 2019). Other regions out of the subtropics, as the Brazilian *Cerrado*, can also expand their area under ICLs, but there the management of the pasture phase is quite different as climate has no cool-season and pasture species are often perennials (Moraes *et al.*, 2019).

Several institutional aspects have also contributed to the development of ICLs in Brazil. Research and extension institutions (i.e. universities, Embrapa, Emater, Epagri, Aliança SIPA, etc.) are constantly investigating new scientifically based strategies and solutions for ICLs, and bringing them to farmers. Federal programs like the ABC plan (low-carbon agriculture) (Costa Jr *et al.*, 2019) grant additional credit to farmers engaged at promoting sustainable farming practices like ICLs. As well farmers, under their associations and cooperatives, are also committed to develop ICLs.

5. Impact on soil organic carbon stocks

In this literature review, we examined changes in SOC stocks in ICLs areas relative to non-grazed controls that represent cover crop only systems, in nine studies conducted in southern Brazil (Table 143). Ryegrass, black oats or their mixtures were the main grazed cover crop species in the cool season; while soybean, maize (for grain or silage) and rice were the main crops during the warm season; all under no-tillage. Ferralsol was the predominant soil type, but two studies were on Planosols. The SOC stocks were determined based on SOC content and soil bulk density and corrected to soil equivalent mass considering a reference treatment that represents the original condition of the study site.

Overall, the studies showed similar or little gains of SOC stocks under moderate- to light-grazing ICLs relative to cover crop only systems, while in cases of intensive grazing and low residues addition, SOC stocks were lower in ICLs. Therefore, moderate to light grazing and high addition of C by crop residues are recommended to maintain the SOC stocks in this region, allowing ICLs to reach higher food production levels without compromising this important C reservoir of the terrestrial ecosystem.

In two sites the SOC was evaluated over time. In a Ferralsol in Castro-PR, Piva *et al.* (2014) measured SOC changes after 3.5 years of ICLs and observed a small increase in C storage, while after 9 years Ramalho *et al.* (2020) observed a tendency of decrease of 0.38 t SOC/ha/yr in relation to a non-grazed site. That decrease was not statistically significant, but could be related to low C addition during the cool-season, as the aboveground matter of ryegrass was removed by intensive grazing (Ramalho *et al.*, 2020). The high original carbon stock of this soil in Castro (a region with lower temperatures, Cfb climate), combined with low and consecutive poor-N residue addition (no legumes presence) were possibly another factors that restricted further increments on SOC by ICLs. Nonetheless, this study highlights the importance of no-tillage either in grazed (ICLs) or non-grazed winter cover crops as a strategy to promote SOC sequestration in relation to conventional tillage (Ramalho *et al.*, 2020). In the second site, in São Miguel das Missões – RS, SOC was evaluated at 5.5, 9 and 13 years after the establishment of ICLs under different grazing intensities. Over the first 5.5 years all grazing intensities resulted in C accumulation (Souza *et al.*, 2008), but after 9 years intensive grazing reduced C stocks (Assmann *et al.*, 2014). By 13 years, both intensive or moderate grazing resulted in C loss, while light intensity resulted in an small accrual of 0.02 t C/ha/yr (Cecagno *et al.*, 2018). In this experiment, the C addition by crop residues was the main factor related to SOC loss or accrual.

As soybean was the only crop cultivated in the warm-season and is characterized by low residue addition, the grazing intensity of ryegrass + black oats cover crops in the cool-season was the main determinant factor to govern any increase in residue addition and to maintain or slight increase SOC stocks in relation to the non-grazed cover crop system (Assmann *et al.*, 2014; Cecagno *et al.*, 2018).

Another study conducted by Piva *et al.* (2020) in the same experiment of Castro-PR showed that in a condition where maize residue was removed as silage, the ICLs can be an alternative to increase SOC stocks due to increase on belowground addition during the first 3.5 years. However, the authors highlight the low additions by aboveground residues in this ICLs (grazed cover crops plus silage removal) are below the requirements to maintain SOC stocks over time and may reduce them in the long-term. In Curitibanos-SC, Ribeiro *et al.* (2020b) studied grazing intensities of black oat and identified that a moderate grazing can increase the SOC stocks in short-time (3.5 yr) in relation to non-grazed oat. This was attributed to belowground additions stimulated by moderate grazing in this soil of a long history of overgrazing (Ribeiro *et al.*, 2020b).

In the two sites of Planosols for rice cultivation, SOC stocks also increased under ICLs, either in the short-term (1.5 yr) (Martins *et al.*, 2017) or in the long-term (9 yr) (Theisen *et al.*, 2017). Those increases were attributed mainly to the replacement of usual fallow period in the cool-season by well managed winter cover crops for grazing (oat or ryegrass), leading therefore to higher net primary production and higher residue addition to soil (Table 139).

The C addition by crop residues is also a crucial factor related to changes in SOC stocks in these subtropical soils under ICLs. For the subtropical croplands of Brazil managed under no-tillage, estimates are that the annual addition of crop residues must be 7-12 t/DM/ha/yr to maintain the C stocks (Bayer *et al.*, 2006; Ferreira *et al.*, 2012). That means that only focusing on the management of the cool-season grazed cover crops it is not enough to achieve those annual input requirements, as most of the aboveground biomass is grazed and only a small ratio of it returns as dung. The majority of ICLs in southern Brazil are based on grazing of oat or ryegrass in cool-season and mainly soybean in the warm-season. Although this scheme is lucrative because of the current soybean market, it is unfortunately characterized by low amount of residues added to soil (Ribeiro *et al.*, 2020a). The choice of a high input crop, such as maize rotating every other warm-season with soybean can be an alternative to increase C additions in the ICLs. Moreover, increasing the residual biomass of the cool-season grazed cover crops by letting a longer regrowth period between the last grazing and the establishment of the next warm-season crop can also increase the C additions in ICLs (Ribeiro *et al.*, 2020a).

Table 143. Soil carbon stocks related to integrated crop-livestock systems in southern Brazil

Location	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Castro – PR	Ferralsol	234.60[1]	0.03^{ns}	3.5	0-100	Intensive grazing (ryegrass-maize)	Piva *et al.* (2014)
Castro – PR	Ferralsol	212.20[1]	-0.38^{ns}	9	0-100	Intensive grazing (ryegrass-maize)	Ramalho *et al.* (2020)
Castro – PR	Ferralsol	67.03[1]	0.22^{ns}	3.5	0-20	Intensive grazing (ryegrass-maize for silage)	Piva *et al.* (2020)
Curitibanos - SC	Ferralsol	135.90[1]	-0.23^{ns}	3.5	0-100	Intensive grazing (black oat-soybean)	Ribeiro *et al.* (2020b)
			0.83*			Moderate grazing (black oat-soybean)	
			0.06^{ns}			Light grazing (black oat-soybean)	
São Miguel das Missões - RS	Ferralsol	42.85[1]	0.19^{ns}	5.5	0-10	Intensive grazing (black oat+ryegrass - soybean)	Souza *et al.* (2008
			0.41^{ns}			Moderate grazing (black oat+ryegrass - soybean)	
			0.57 ^{ns}			Light grazing (black oat+ryegrass - soybean)	
São Miguel das Missões - RS	Ferralsol	60.42[1]	-0.96*	9	0-20	Intensive grazing (black oat+ryegrass - soybean)	Assmann *et al.* (2014)

Location	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
			-0.05^{ns}			Moderate grazing (black oat+ryegrass - soybean)	
			-0.01^{ns}			Moderate-Light grazing (black oat+ryegrass - soybean)	
			-0.10^{ns}			Light grazing (black oat+ryegrass - soybean)	
São Miguel das Missões - RS	Ferralsol	54.70[1]	-0.20^{ns}	13	0-20	Intensive grazing (black oat+ryegrass - soybean)	Cecagno *et al.* (2018)
			-0.12^{ns}			Moderate grazing (black oat+ryegrass - soybean)	
			0.02^{ns}			Moderate-Light grazing (black oat+ryegrass - soybean)	
			0.02^{ns}			Light grazing (black oat+ryegrass - soybean)	
Cristal - RS	Planosols	16.18[2]	1.82^{ns}	1.5	0-10	Moderate grazing (ryegrass - rice)	Martins *et al.* (2017)
			-0.33^{ns}			Moderate grazing (ryegrass - soybean)	
Pelotas - RS	Planosols	28.61[2]	0.64^{na}	9	0-20	Light grazing (ryegrass+oat – soybean and maize)	Theisen *et al.* (2017)

[1] The baseline is in the non-grazed pasture, used only as cover crop. [2] Rice monocropping in warm-season, fallow in cool-season. Statistics from the original studies were presented as not significant (^{ns}), significant (*) or not available (^{na}).

6. Other benefits of the practice

6.1. Improvement of soil properties

In terms of physical properties, the ICLs under light grazing of cover crops improved the soil structural quality (Auler *et al.*, 2017), aggregation (Souza *et al.*, 2010a), macroporosity, pore size and connectivity, and reduced bulk density (Bonetti *et al.*, 2019), compared to intensive grazing. Such improvements in soil physical properties were related to the increase in residues input, root development and in SOC concentration (Auler *et al.*, 2017; Bonetti *et al.*, 2019). According to Ambus *et al.* (2018), ICLs soil under moderate grazing of cool-season cover crops has an interesting capability of physical regeneration due root growth and exudation, so that the soil compaction by animal trampling does not persist to the grain crop phase. Furthermore, ICLs with diverse grazed cover crop species (ryegrass, black oats, white clover and red clover) can reduce soil bulk density and increase macroporosity in relation to monocrop, even under a high stocking rate (Silva *et al.*, 2014).

Soil chemical properties are often boosted by the ICLs. Moderate grazing stimulates cover crop regrowth and uptake of N, P, K, Ca and Mg from soil. Therefore, most of the nutrients ingested by animals return to soil as dung and urine, and together with litter can be released to soil and be available to summer cash crops (Assmann *et al.*, 2015; Assmann *et al.*, 2017a; Assmann *et al.*, 2017b; Deiss *et al.*, 2020). The N input is highly relevant in these case, since cattle have a low N efficiency use, therefore 70 to 95% of the N ingested is excreted in urine and dung (Oenema *et al.*, 2005). Other nutrients, like Ca and Mg, and soil pH were also increased by the ICLs, mainly due the increased soil porosity that favors the transportation of small lime particles and the leaching of Ca^{+2} and Mg^{+2} down in the soil profile, also reducing acidity (Deiss *et al.*, 2020). Moderate grazing in ICLs also reduces Al toxicity due to complexation by organic compounds cumulated over long-time of grazing management (Martins *et al.*, 2020).

In soil biological properties, the ICLs increase the diversity of soil mesofauna in the cool-season (Zagatto *et al.*, 2017). Moderate to light grazing of cool-season cover crops in ICLs also increase microbiological diversity and activity in relation to no grazing (Chávez *et al.*, 2011). The input of animal excreta and residues (roots and aboveground) are related to the increase in soil microbial biomass and basal respiration (Souza *et al.*, 2010b; Moraes *et al.*, 2014a).

6.2 Minimization of threats to soil functions

Table 144. Soil threats

Soil threats	
Soil erosion	ICLs are conducted under no-tillage practice, which maintain soil cover by crops and straw, reducing the potential of wind and water erosion (Farias *et al.*, 2020). Also, losses of soil and water by erosion were lower in ICLs than crop only system (Coblinski *et al.*, 2019).

Soil threats	
Nutrient imbalance and cycling	Grazing animals enhance biogeochemical cycles (Assmann *et al.*, 2014; Assmann *et al.*, 2015). Nitrogen applied to cool-season grazed cover crops can be recycled and uptake by grain crop in the warm-season, and vice-versa (Bernardon *et al.*, 2020). See section 6.1.
Soil contamination / pollution	Moderate and light grazing in ICLs reduced weed seed bank and richness compared to a non-grazed system, therefore potentially reducing the use of herbicide that could led to soil contamination (Schuster *et al.*, 2016).
Soil acidification	ICLs reduces Al toxicity (Martins *et al.*, 2020) and increases soil pH (Deiss *et al.*, 2020). See section 6.1.
Soil biodiversity loss	ICLS increases soil microbial (Chávez *et al.*, 2011) and mesofauna (Zagatto *et al.*, 2017) diversity. See section 6.1.

6.3 On provision services (e.g. Food/Fuel/Feed/Timber)

Many studies reported no effects of ICLs on yields of soybean grain (Souza *et al.*, 2010b; Peterson *et al.*, 2019; Pilecco *et al.*, 2019; Farias *et al.*, 2020; Ribeiro *et al.*, 2020a), maize grain (Sartor *et al.*, 2018; Ribeiro *et al.*, 2020a) or silage (Balbinot *et al.*, 2011; Piva *et al.*, 2020), and common beans grain (Balbinot *et al.*, 2011), in relation to non-grazed cool-season cover crop areas in southern Brazil. However, despite of no increase on grain/silage yields, those ICLs increase food production due to beef and/or milk production by grazing animals (Carvalho *et al.*, 2010; Wesp *et al.*, 2016). In the case of sheep grazing in the ICLs, there also a gain in wool and meat production (Farias *et al.*, 2020).

In the region, some ICLs include tree cultivation, in integrated crop-livestock-forest (ICLFs, also defined in this manual as Agrosylvopastoralism). In these systems, there are also timber production and other wood resources. The main wood species used are *Grevillea robusta*, *Eucalyptus dunnii* and *Eucalyptus benthamii* (Dominschek *et al.*, 2018; Pontes *et al.*, 2018).

6.4 Mitigation of and adaptation to climate change

The ICLS can stimulate the uptake methane (CH_4) into soil, but it is confined to systems with moderate to light grazing (Ribeiro *et al.*, 2020b) or low nitrogen application rates to the cool-season grazed cover crops (Piva *et al.*, 2019). In addition, the soil nitrous oxide (N_2O) emission is lower in grazed than in non-grazed cover crops (Pilecco *et al.*, 2019; Piva *et al.*, 2019). This fact is mainly due to the higher use of nitrogen during cover crop regrowth (Piva *et al.*, 2019) or by the early sowing of ryegrass (Pilecco *et al.*, 2019). The ICLs with moderate grazing can decrease the net global warming potential by 98% compared to non-grazed cover crops (Ribeiro *et* *al.*, 2020b). ICLFs, on the other hand, have a high potential for sequestering atmospheric CO_2 in trees and can offset the enteric CH_4 emission (Dominschek *et al.*, 2018).

6.5 Socio-economic benefits

The diversification of production in ICLs, with grain/biomass and beef/milk/wool allows income diversification and reduced risks (Carvalho *et al.*, 2018). The livestock production in less vulnerable to climatic variations than soybean production, thus the ICLs brings economic resilience (Szymczak *et al.*, 2020). ICLs also increase job creation and stimulate development of industries at regional level (Theisen *et al.*, 2017). The ICLs reduces the uses of pesticides, which reduces costs and also risks to human health.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 145. Soil threats

Soil threats	
Nutrient imbalance and cycling	Urine and dung deposition by grazing animals increase NH4+ and NO3- availability in soil leading to N losses and a direct source of N2O emission to atmosphere (Piva *et al.*, 2014). Intensive grazing can result In SOC depletion due to less residue addition and result in loss of nutrients compared to a non-grazed cover crop (Ribeiro *et al.*, 2020a; Ribeiro *et al.*, 2020b).
Soil compaction	In ICLs under intensive grazing, animal trampling increases soil bulk density and reduces its structural quality (Auler *et al.*, 2017; Bonetti *et al.*, 2019; Piva *et al.*, 2019). Shallow compaction by grazing may occur during the wet conditions of the cool-season, mainly in clayey soils with high moisture (Auler *et al.*, 2017; Bonetti *et al.*, 2019).
Soil water management	Intensive grazing reduces soil water storage mainly due to less residue retention than a non-grazed cover crop, thus causing water stress to summer cash crops (Cecagno *et al.*, 2017; Peterson *et al.*, 2020).

7.2 Increases in greenhouse gas emissions

Information about GHG emissions in ICL systems are given in Table 147. Most of the emissions generally come from soil (N_2O and CH_4) and enteric fermentation (Ribeiro *et al.*, 2020b). The soil N_2O emission was attributed to higher nitrogen availability through nitrogen fertilization (Piva *et al.*, 2019), soybean leaf fall and release of N (Pilecco *et al.*, 2019; Ribeiro *et al.*, 2020b) or excreta deposition (Piva *et al.*, 2014).

The soil CH_4 emission can occur under intensive grazing (Ribeiro *et al.*, 2020b) or under high nitrogen fertilization rates (Piva *et al.*, 2019). The exposure of the soil surface under intensive grazing of cool-season cover crops can promote stress to methanotrophic bacteria while nitrogen fertilization can inhibit the CH_4 uptake by the competition for methane monooxygenase enzyme, thus increasing CH_4 emission to atmosphere.

The CH_4 emission via enteric fermentation is related to the number of grazing animals, with higher emissions in intensive grazing systems (Savian *et al.*, 2014; Souza Filho *et al.*, 2019; Ribeiro *et al.*, 2020b).

7.3 Conflict with other practice(s)

The ICLs might have some conflict with other agricultural land uses as cool-season cash crops like wheat and barley (Fontoura *et al.*, 2019), and with cover crop systems used to produce green manure during the cool-season (fodder radish, vetch), fostering the grain yields from the warm-season (Veloso *et al.*, 2018; Piva *et al.*, 2021).

7.4 Decreases in production (Food/fuel/feed/timber/fibre

As highlighted in compilation of subtropical ICLs studies by Moraes *et al.* (2014b), there are no reductions on warm-season crop yields when soil fertility is adequate and with a moderate grazing of cover crops in the cool-season.

8. Recommendations before implementing the practice

Soil sampling and correction of soil fertility and acidity is recommended, as is the construction of physical barriers to control the runoff rainwater (i.e. terraces) and use of other soil conservation practices (cross-slope farming, crop rotation). The fertilization system may be considered in order to increase nutrients efficiency and reduce its loss, with a positive increase in both cool-season grazed cover crops and warm-season grains production (Sartor *et al.*, 2018; Bernardon *et al.*, 2020; Farias *et al.*, 2020).

9. Potential barriers for adoption

Table 146. Potential barriers to adoption

Barrier	YES/NO	
Biophysical/ Natural resource	Yes	Livestock production is limited to 4-5 months during the cool-season cover crop development and it more land is necessary to sustain the animals in the warm-season or an effective market of purchase/sale of animals (Moraes *et al.*, 2019; Szymczak *et al.*, 2020).
Cultural / Social	Yes	There are still traditional farms with extensive use of pastures and low investment of inputs and technology, focused only in livestock production (Martins *et al.*, 2015; Anghinoni *et al.*, 2018). Many farmers can be resistant to introduction of livestock in crop areas, uninformed about empirical factors that grazing can cause soil compaction, reduction in residue input and nutrients depletion (Moraes *et al.*, 2019).
Economic	Yes	Other agricultural uses that result in alternative income sources. See section 7.3.
Institutional	No	There are many institutions are involved in research and extension related to diffusion of ICLs in southern Brazil. See section 4.

Table 147. Greenhouse gases emissions related to integrated crop-livestock systems in southern Brazil

Location	Soil type	Enteric CH_4 emission (kg CO_2eq/ha/day)	Soil		ICL system details	Evaluated treatment	Reference
			N_2O emission	CH_4 emission			
			(kg CO_2eq/ha/yr)				
Castro - PR	Ferralsol	na[1]	844[2]	15	Beef cattle (ryegrass/maize)	Intensive grazing	Piva *et al.* (2014)
Curitibanos - SC	Ferralsol	6.5	1,083	30	Beef cattle (black oat/soybean)	Intensive grazing	Ribeiro *et al.* (2020b)
		5.2	916	22		Moderate grazing	
		2.6	791	-34		Light grazing	
Eldorado do Sul - RS	Ultisol	20.4	na	na	Sheep (ryegrass/maize or soybean)	Continuous light grazing	Savian *et al.* (2014)
		28.1	na	na		Continuous moderate grazing	
		22.3	na	na		Rotational light grazing	
		32.0	na	na		Rotational moderate grazing	
Guarapuava - PR	Ferralsol	na	134	-22.10	Sheep (ryegrass + black oat/maize or bean)	0 kg N/ha	Piva *et al.* (2019)
		na	530	-21.42		75 kg N/ha	
		na	626	-8.84		150 kg N/ha	
		na	238	-18.70		Grazed	
		na	623	-16.32		Ungrazed	
Ponta Grossa - PR	Cambisol/ Ferralsol	18.4	na	na	Beef cattle (ryegrass + black oat / maize or soybean)	Eucalyptus presence + 90 kg N/ha	Pontes *et al.* (2018)
		17.3	na	na		Eucalyptus presence + 180 kg N/ha	
		26.5	na	na		Eucalyptus absence + 90 kg N/ha	
		28.2	na	na		Eucalyptus absence + 180 kg N/ha	
São Miguel das Missões - RS	Ferralsol	24.1	na	na	Beef cattle (black oat / soybean)	Intensive grazing	Souza Filho *et al.* (2019)
		17.7	na	na		Moderate grazing	
		12.0	na	na		Moderate-light grazing	
		8.4	na	na		Light grazing	
Santa Maria - RS	Ultisol	na	385	na	Beef cattle (ryegrass / soybean)	Ryegrass early sowing in soybean (R7)	Pilecco *et al.* (2019)
		na	472	na		Ryegrass sowing after soybean harvest	

[1]Not available; [2]Sum of N_2O emission from soil and excreta; Estimative of CO_2eq emissions were based in N_2O GWP of 298 and CH_4 GWP of 34.

Photos

Photo 68. Representative landscape of an ICLs in Southern Brazil

In (A) Holstein heifers grazing black oat cover crop over maize residues in Curitibanos – SC (photo from Felipe Bratti - 2017). In (B) Charolais and Angus cross-breed heifers grazing black oat cover crop after soybean in Campos Novos – SC.

Photo 69. Model of an ICLs crop rotation to increase residue addition to soil in Southern Brazil

With black oats grazing during the cool-season (left) and soybean (above right) and maize (below right) rotating every other warm-season– 2017 and 2018.

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36. Agroforestry, silvopastoral systems and water funds initiatives contribute to improve soil capacity to remove and store carbon in Colombia

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1. Related practices

Forest restoration, Agroforestry (cacao), Silvopastoralism

2. Description of the case study

The Agriculture, Forestry and Other Land Use (AFOLU) sector emits around 24% of total emissions globally (IPCC, 2019), but in Colombia its contribution increases to 62% of country's GHG emissions, mainly due to deforestation, forest degradation and conventional cattle ranching (IDEAM, 2016). Despite of the importance of soils as one of the largest organic carbon (C) reservoirs in tropical ecosystems, its potential to mitigate climate change needs to be better assessed (Don, Schumacher and Freibauer, 2011).

Activities on conservation, restoration and sustainable production would contribute significantly to increase the capacity of soils to sequester and store C in natural and human-modified ecosystems (Bossio *et al.*, 2020; Berenguer *et al.*, 2014), and to improve human well-being of local communities around the world (Griscom *et al.*, 2020). Additional and more accurate information on soil capacity to remove and store C are required to catalyze conserving, restoring and managing activities into soil C markets.

Here we present results on the contribution of the projects Agroforestry for Conservation (A4C), Bogota Water Fund (BWF) and Sustainable Cattle Ranching (SCR) to mitigate climate change in Colombia by capturing and storing C in soils of areas where activities on forest conservation, forest restoration and implementation silvopastoral and cacao systems were implemented.

Agroforestry for Conservation

The Agroforestry for Conservation (A4C) project[7] aims to reduce deforestation in the Colombian Amazon by promoting activities on forest conservation and passive restoration, and the implementation of agroforestry systems, including the production of cacao, among local farmers and indigenous communities (Photo 70). The A4C project started in 2018 and has been developing land use management tools and monitoring schemes to support the implementation of environmentally sustainable production alternatives on 150 farm owners and 4 indigenous territories located in the Caquetá department, the jurisdiction with the highest rates of deforestation historically in Colombia.

The jurisdiction of Caquetá is in the Amazon region of Colombia, where lowland tropical wet forests originally occupied around 90% of the territory, and mountain wet forests, at the transition with the Andes region, occupied the rest of the area. Since the second half of the 20th century the Colombian Government implemented a strategy to colonize and establish settlements in the Colombia Amazon (World Bank, 1967), which resulted in the accelerated expansion of the agricultural frontier through unplanned deforestation of huge forest areas that were converted mainly into grasslands.

Bogota Water Fund

The Water Fund initiative was proposed in 2012 by the Nature Conservancy (TNC) to align public and private stakeholders to leverage financial and governance mechanisms around water security in strategic watersheds in Colombia and other countries (TNC, 2012). The BWF was founded in 2009 by TNC, the National System of Protected Areas of Colombia, the Water Supply Company of Bogota, and Bavaria from private sector, with the aim of guaranteeing water security for the city of Bogota and close municipalities. Since then, the BWF project has been promoting and supporting the implementation of activities on forest conservation, active and passive forest restoration, and sustainable production in watersheds that supply water to Bogota (Photo 71).

The BWF project scope is local and is focused on activities on conservation and restoration of Andean wet forests and paramo ecosystems located within farms participating in the project. Cattle grazing on pasture areas established during the first decades of the 20th century after forest-to-pasture conversion is the predominant land use in the BWF project area[8].

Sustainable Cattle Ranching Project

In 2010, the Sustainable Cattle Ranching (SCR) Project[9] was proposed with the objective of promoting the improvement of livestock practices in Colombia through the adoption of sustainable practices that contribute to the reduction of GHG emissions, the conservation of biodiversity in livestock systems, and the increase of livestock productivity. The project seeks to promote the adoption of silvopastoral systems, live fences and

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[8] The carbon monitoring was funded by Rodney Johnson and Katharine Ordway Stewardship Endowment (RJ KOSE)

[9] Funded by the Global Environment Facility and the Department for Business, Energy and the Industrial Strategy of the UK government

scattered trees in pastures, as well as to conserve primary and secondary forest, with the aim of improving natural resource management, increase the provision of environmental services (biodiversity, soil, water and carbon sequestration), and improve productivity of the participating farms. The project also provides technical assistance to design and implement land use conversion plans promoted by the project, through regional technical assistance teams.

The SCR project has a subnational scope, and has been implemented in the Andean, Caribbean and Orinoco regions of Colombia, where the project focused on promoting activities on conservation of primary and secondary forests, and the implementation of three kind of silvopastorals systems: i) scattered trees in pastures, ii) live fences, and iii) intensive silvopastoral systems (Photo 72).

3. Context of the case study

A4C project

The A4C project is located at the west of the Colombian Amazon where the major landforms are low-gradient foot slopes and dissected plains, extending eastward between 800 – 200 m above sea level. Predominant soils at the foothills and lower sectors are Inceptisols and Oxisols, respectively. Mean annual precipitation and mean annual temperature in the region where A4C is located are 3 700 mm and 26 °C, and the dominant natural forest is the Tropical Moist Forest, which stores around 136.6 tC/ha and 27.5 tC/ha in the above- and below-ground biomass, respectively (Phillips *et al.*, 2014). Extensive cattle ranching is the main land use in pastures established after deforestation in this region (Bowman *et al.*, 2012), highlighting the importance of promoting sustainable practices that reduce the pressure on the Amazonian Forest in Colombia. Therefore, in A4C project case-study we aim to assess the contribution of forest restoration and agroforestry systems of cacao to increase soil potential to remove and store carbon.

Changes in carbon stocks were monitored following the chronosequence approach in which monitoring along time of one place is replaced by monitoring places with different stages of establishment of a land-cover conversion. For the A4C project, changes in soil organic carbon (SOC) were monitored in three different chronosequences:

- Deforestation: 20-year forest-to-pasture conversion,
- Forest restoration: 20-year pasture-to-forest conversion,
- Agroforestry systems of cacao 10-year pasture-to-cacao cropland conversion.

BWF project

The BWF project is located at the western branch of the Colombian Andes, where landscape is dominated by mountain landforms extending northward between 2700 – 3200 m above sea level. Predominant soils at this region are Inceptisols and organic matter content is around 60%. Mean annual precipitation and mean annual temperature in the region where the BWF project is located are 1800 mm and 12 °C, and the dominant natural forest is the Mountain Moist Forest, which stores around 72.7 tC ha^{-1} and 17.4 tC ha^{-1} in the above- and below-ground biomass, respectively (Phillips *et al.*, 2014). Conventional cattle ranching and potato crops are the predominant land uses in the BWF project area, so in this case-study we aim to assess the contribution of forest restoration to increase soil potential to remove and store carbon. Also, changes in soil organic carbon (SOC) were monitored in one chronosequence:

- Forest restoration: 40-year pasture-to-forest conversion.

SCR project

The SCR project has been implemented in three different regions of Colombia: Andes, Caribbean and Orinoco. Landscape in the Andean region is dominated by mountain landforms with an altitude between 1800 – 2700 m above sea level, where Inceptisols are the predominant type of soils and mean annual precipitation and temperature are within the ranges of 1500 – 2700 mm and 14 – 19 °C. In the Caribbean region, on the other hand, lowland plains dominate the landscape at an altitude of around 80 m above sea level. At this region the predominant type of soils are Alfisols, and mean annual precipitation and temperature are 1100 mm and 26 °C, respectively. Finally, foot slopes and dissected plains dominate the landscape of the Orinoco region where the SCR project has been implemented, and the main soil types are Oxisols. The altitude of the region is 200 m above sea level and mean annual precipitation and temperature 3200 and 25 °C.

Natural forests located at these three regions are Mountain Moist Forest (72.7 t C ha^{-1} and 17.4 t C ha^{-1} in AGB and BGB) and Pre-Mountain Moist Forest (57.0 t C ha^{-1} and 13.8 t C ha^{-1} in AGB and BGB) in the Andean region, Tropical Dry Forest (48.1 t C ha^{-1} in AGB and 11.5 t C ha^{-1} in BGB) in the Caribbean region, and Tropical Moist Forest (136.6 t C ha^{-1} in AGB and 27.5 t C ha^{-1} in BGB) in the Orinoco region (Phillips *et al.*, 2014). Conventional cattle ranching is the main land use in the SCR project regions, so for this case-study we aim to assess the contribution of forest restoration and silvopastoral systems, corresponding to scattered trees in pastures, life fences and intensive silvopastoral systems, to increase soil potential to remove and store carbon. As well as in the previous case-studies, changes in soil organic carbon (SOC) were monitored in three different chronosequence:

- Scattered trees: 9-year pasture-to-scattered trees in pastures conversion,
- Life-fences: 9-year pasture-to-life fences conversion,
- Intensive silvopastoral systems: 9-year pasture-to-intensive silvopastoral systems conversion.

4. Possibility of scaling up

Scaling up sustainable practices on forest restoration, agroforestry (cacao) and silvopastoral systems implemented by the A4C, BWF and SCR projects would be possible by designing and strengthening multi-stakeholders dialog platforms, in areas where these practices can be applied by local producers through community-based and private associations (e.g. Cattle Ranchers Association of Colombia – Fedegan), or regional or national programs focused on local producers (e.g. Program Vision Amazonia). The A4C project, for example, might be replicated in other hotspots of deforestation in the Colombian Amazon to reduce the pressure on forests, and both the BWF and SCR project can contribute to restore degraded pasture areas and improve livelihood, water supply and biodiversity in various locations of Colombia.

Practices implemented by the A4C, BWF and SCR projects might also be scaled up to other countries in Latin America and outside the region, as an alternative to reduce deforestation or improve soil degradation in productive places in accordance with national circumstances. One example of the possibility to scale up these practices is the Water Fund Network, which includes members from Africa, Asia, Latin America and North America that support the implementation of water funds initiatives around the world on legal, technical, market and other aspects[10].

5. Impact on soil organic carbon stocks

For all case-studies we followed the *Protocolo para la Estimación y el Monitoreo del Carbono en Coberturas Forestales y no Forestales de Colombia*, developed by TNC (2018), which is based on the National Forest Inventory of Colombia. Therefore, in order to determine SOC changes associated with activities on forest conservation, forest restoration and implementation silvopastoral and cacao systems we established monitoring plots at each stage of the chronosequences mentioned above. The design of each plot includes sampling areas to measure the above-ground biomass of big trees (i.e. DBH ≥ 10 cm), small trees (i.e. 1 ≥ DBH < 10 cm), herbs, and soil organic carbon.

Soil organic carbon was sampled at each plot, where the soil samples were collected at 0-10 cm, 10-20 cm and 20-30 cm depth using an AMS Soil Core Sampler. Soil samples were packed in plastic bags and carried to the Laboratory of Ecology of the Universidad Javeriana, in the case of the BWF project, and to the Analytical Services Laboratory at the International Center of Tropical Agriculture, in the case of A4C and SCR projects. Once at the lab samples were oven-dried at 60 °C, and sub-samples of 18.0 mg were taken after soils were ground and passed through a 2 mm sieve. Total organic C content was determined by the dry combustion method (at 900 °C), using a PE 2400 Series II CHNS/O Analyzer calibrated with certified acetanilide (C_8H_9NO), as well as bulk density.

Results from each case-study are described next:

A4C project

In the cases of the A4C project, SOC stocks down to 30 cm depth decreased from 56.7 ± 2.6 tC/ha to 48.5 ± 2.9 tC/ha when the Amazonian forests is intervened, and as Navarrete *et al.* (2016) demonstrated, forest-to-pasture conversion (i.e. deforestation and pastures establishment) leads to a decreased by 20% after 20 years of pasture establishment. However, when activities on forest restoration were implemented in degraded pastures SOC stocks increased from 37.9 ± 1.6 tC/ha to 47.4 ± 2.0 tC/ha after 20 years of forest growth. On the other hand, there was no significant changes in SOC stock after 10 years of cocoa establishment.

As expected, a larger amount of SOC was found in the top 0-10 cm layer in all land covers in the Colombian Amazon, followed by the 10-20 cm and 20-30 cm layers. The same pattern of total SOC reduction after forest degradation and SOC increase after forest restoration was also detected in each one of the three soil layers, as well as the unchanged C stocks after 10 years of cocoa crops establishment. Navarrete *et al.* (2016) previously reported the effects of deforestation and pastures establishment on the top 0-10 cm, 10-20 cm and 20-30 cm layers.

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[10] https://waterfundstoolbox.org/network

BWF project

Total SOC stocks down to 30 cm depth in the BWF project averaged 182.0 ± 14.9 tC/ha in pastures, and increased to 285.6 ± 28.6 tC/ha after 40 years forest restoration, representing around 70% of the total C stock of the ecosystem compared to the above-ground biomass. SOC stocks significantly increased during the pasture-to-forest conversion in the top 0 – 10, 10 – 20 and 20 – 30 cm layers, where forests sites exhibit 15 – 56% more SOC in the 0 – 10 cm layer than the pasture, 25 – 53% in the 10 – 20 cm *layer and 56 – 63% in the 20 – 30 cm layer.*

SCR project

SOC stocks down to 30 cm depth significantly increased only in life fences among regions where the SCR project was implemented. In this type of establishment, SOC changed from 4.8 ± 0.4 tC/ha in pastures to 8.2 ± 1.3 tC/ha in the Andean region after nine years of implementation, whereas it increased from 5.8 ± 0.5 tC/ha to 16.7 ± 1.7 tC/ha in the Caribbean region during the same time. No significant changes were detected in SOC stocks during pasture-to-scattered trees in pastures and pasture-to- intensive silvopastoral systems conversions after nine years of SCR project implementation.

Table 148. Changes in soil organic carbon stores

Location	Climate zone	Soil type	Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	More information	Reference
A4C project: Colombian Amazon	Tropical wet lowlands	Inceptisols and Oxisols	37.9	0.5	20	20-year pasture-to-forest conversion	This study
BWF project: Colombian Andes	Tropical wet highlands	Inceptisols	182.0	2.6	40	40-year pasture-to-forest conversion	This study
SCR project: Colombian Andes	Tropical moist highlands	Inceptisols	4.8	0.4	9	9-year pasture-to-life fences conversion	This study
SCR project: Colombian Caribbean	Tropical dry lowlands	Alfisols	5.8	1.2	9	9-year pasture-to-life fences conversion	This study

6. Other benefits of the practice

6.1. Improvement of soil properties

In most projects SOC increase was always correlated to a reduction in soil compaction, measured as soil bulk density. In the case of the BFW project, soil bulk density tended to decrease during the pasture-to-forest conversion, from 0.69 ± 0.02 g/cm^3 at the pastures to 0.53 ± 0.04 g/cm^3 at the 40-year-old Andean forests. In the case of the SCR project, on the other hand, after nine year of implementation soil bulk density also decreased from 1.23 ± 0.05 g/cm^3 at the pastures to 1.01 ± 0.07 g/cm^3 at the life fences areas in Andean region, and from 1.57 ± 0.03 g/cm^3 to 1.30 ± 0.07 g/cm^3 in the Caribbean region. No significant changes in bulk density were detected in the A4C project (on average 1.10 ± 0.04 g/cm^3).

6.2 Minimization of threats to soil functions

Table 149. Soil threats

Soil threats	
Soil compaction	Activities presented here contribute to reduce soil compaction produced by livestock trampling or the use of machinery. An increase in soil compaction was detected 20 years after deforestation and pasture establishment in the Colombian Amazon. An increase of SOC is detected in areas where soil compaction decreased, possibly associated with the improvement of soil organic matter input, porosity, and water infiltration.

6.3 Climate change mitigation and adaptation and Socio-economic benefits

Additional and more accurate information on soil capacity to remove CO_2 in restoration and sustainable production activities, such as those implemented by the A4C, BWF and SCR projects, is required to promote these initiatives as potential soil carbon market opportunities for local communities. This information can also be used to show the contribution of initiatives focused on implementing sustainable practices to meet Colombian commitment to reduce their emission under the Paris Agreement, and to update, an even increase the ambition of, Colombia′s nationally determined contributions (NDCs). Colombian NDCs also include commitments on adaptation by 2030, aiming to increase the adoption of climate change plans to cover 100% of the Colombian territory, implement a national plan of adaptation, or increase the extent of protected areas in the Country. The Ecosystem-based Adaptation (EbA) approach is focused on using biodiversity and ecosystem services as one strategy to help people to be adapted to climate change risks. According to (MADS, 2018), silvopastoral systems are one of EbA’s alternatives of climate change adaptation, and represent a benefit to local communities by improving their incomes and to ecosystems by contributing to tackle climate change.

8. Potential barriers for adoption

Potential barriers for the adoption of sustainable practices on forest restoration, agroforestry (cacao) and silvopastoral systems implemented by the A4C, BWF and SCR projects are presented below:

Table 150. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	There is a robust set of country-specific information on land suitability and other biophysical data to determine the best places to implement sustainable practices.
Cultural	Yes	Some practices, such as conventional cattle ranching, have a deep cultural component in Colombia, which might become a barrier for implementing sustainable practices.
Social	No	There wouldn't be social barriers if sustainable practices are accessible to most of landowners and represent improvements in their livelihood.
Economic	Yes	Implementing sustainable practices would represent an additional investment for landowners, and incentives related to economic benefits associated to carbon markets, including soil, are still poorly developed.
Institutional	No	National, regional and local institutional arrangement in Colombia facilitates the adoption of sustainable practices.
Legal (Right to soil)	Yes	In a large portion of the country land tenure (i.e. property legal rights) is not clear.
Knowledge	Yes	Additional and more accurate information on soil capacity to remove and store C in activities on conservation, restoration and sustainable production is required.
Natural resource	No	Natural resources are not a barrier for adopting practices such as those implemented by A4C, BWF and SCR projects, although their implementation should be based on previous studies on land suitability.

Photos

Photo 70. Agroforestry of cacao and forest restoration in the Colombian Amazon implemented by the project Agroforestry for Conservation the jurisdiction (department) of Caquetá, Colombia

Photo 71. Silvopastoral systems in the in the Caribbean region implemented by the project Sustainable Cattle Ranching in the Andes, Caribbean and Orinoco regions of Colombia

Photo 72. Forest restoration in the Colombian Andes implemented by the Bogotá Water Fund project

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37. 30 years of conservation agriculture practices on Vertisols in Central Mexico

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1. Related practices

Conservation agriculture, crop rotations, organic mulch, reduced tillage

2. Description of the case study

Vertisols, in the region known as Bajio in Mexico, occupy a surface of 8.6 percent and possess a high agricultural potential (INEGI, 2007). This type of soils covers large areas, but the application of intensive agricultural practices has caused serious deterioration (Báez-Pérez *et al.*, 2012b; Torres-Guerrero *et al.*, 2016). Their fertility improvement depends upon the carbon accumulated along the soil profile. Agricultural conservation practices have been implemented as an option to increase the content of soil organic carbon (SOC) as these practices are applied retaining crop residues, minimizing tillage and rotating crops. The objective of this experiment was to evaluate the SOC accumulation as affected by conservation practices in Vertisols under agriculture for over 30 years. The site is located in the municipality of Valle de Santiago at the Technological Development Center in Villadiego state of Guanajuato. Crop rotation consisted on planting maize (*Zea mays* L.*)* or sorghum (*Sorghum bicolor* L. Moench) as summer crop and wheat (*Triticum aestivum* L.) or barley (*Hordeum vulgare* L.) as winter crop. Urea was applied as main source of nitrogen to an average rate of 300 units per ha. Fertilizer rates for sorghum and corn, with availability of irrigation in spring-summer, were around 300 and 400 units of N per ha respectively, and 230 units of N per ha for barley and wheat in autumn-winter. Soil samples were collected to a 30 cm depth in plots with crop residue retention for 0, 3, 6, 11, 24 and 30 years. SOC showed a linear tendency to increase over time (R^2=0.95). This parameter, at the onset of the experiment, was 0.72 percent and increased to 2.64 percent after 30 years of cropping. According to results, the rate of accumulation was 1.9 t SOC/ha/yr. The amount of crop residues (maize or sorghum plus wheat or barley) left as stubble was about 20 t/ha/yr. It is estimated that these types of soils can accumulate about 80 t/ha of crop residues over to 30 cm depth (Tinoco-Páramo, 2013).

3. Context of the case study

This experiment was carried out at the Technological Development Center in the municipality of Villadiego (20°23′31″ N, 101°11′21″ W, 1 723 m.a.s.l) state of Guanajuato (Figure 34). Climate is classified as BS1hw(w)(e)g (Garcia, 1984), average annual temperature is 20.6 °C and annual rainfall 597 mm. According to the World Reference Base system, the soils in assessment corresponds to a pellic-mazic qualifiers of Vertisol, depth is greater than 1 m and soil texture is clay 60 percent, silt 30 percent and sand 10 percent.

Figure 34. Technological Development Center, Valle de Santiago, Guanajuato, Mexico. Source: Aurelio Báez Pérez, Agustín Limón Ortega, Angélica Bautista Cruz Bertha Patricia Morales Zamora

4. Possibility of scaling up

The study can be scaled to other Vertisols in other sub-humid lands with intensive agricultural use (Cotler *et al.*, 2016).

5. Impact on soil organic carbon stocks

After thirty years of implementation of conservation practices the SOC stock has increased to 79.5 t C/ha, that is 58 t/ha more SOC with respect to the baseline. The rate of increase was greater in the first three years and then decreased afterwards (Table 151). Báez Pérez *et al.* (2002) have previously documented this trend. The accumulation of SOC during the first years is linear, and afterwards decreases following a non-linear trend, which can be adjusted to a logarithmic or polynomial model as shown in Figure 35.

Table 151. Evolution of SOC stocks on the study site in Bajio, Central Mexico

C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Reference
21.5	0.00	0	Baéz-Pérez (2017); Tinoco-Parámo (2013)
33.5	4.00	3	
42.6	1.52	6	
57.5	1.35	11	
65.5	0.33	24	
79.5	0.47	30	

Climate is warm temperate dry according to the IPCC classification

Soils are pellic-mazic Vertisol

SOC stocks have been measured at 0-30 cm depth

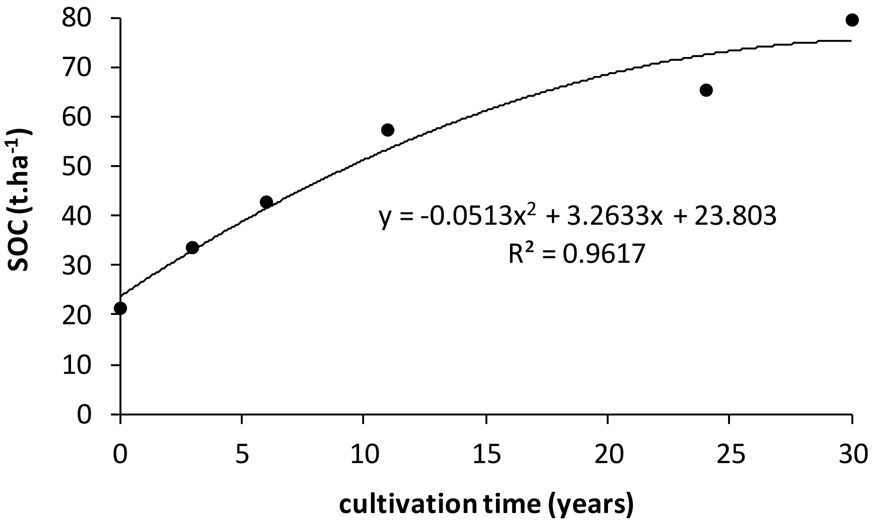

Figure 35. Relationship between SOC accumulation and years under conservation agriculture practices

6. Other benefits of the practice

6.1. Improvement of soil properties

Soil structure improved specifically micro porosity, water infiltration, and soil compaction. Bulk density was reduced from 1.2 to 0.95 t/m^3 (Figure 36).

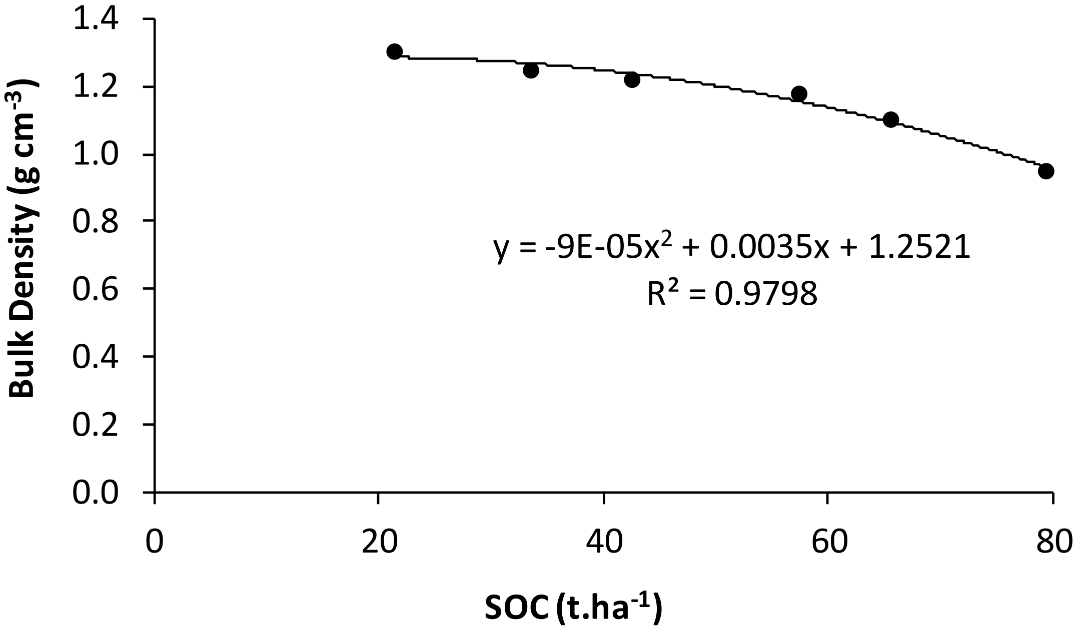

Figure 36. Relationship between apparent bulk density and SOC

Improvement of chemical soil properties by means of conservation agriculture was registered, mainly pH reduction, from alkaline to neutral (Báez Pérez *et al.*, 2017), a significant reduction in electrical conductivity, and therefore, a better availability of nutrients in the soil.

The increase of soil organic matter due to conservation agriculture improves the population and biodiversity of soil organisms. This benefit increases the content of humic substances giving place to accumulation of recalcitrant carbon, which is stored in the soil for a long period (García-Silva *et al.*, 2005). The biological control of plagues and diseases in the agro-ecosystem is feasible (Bahena-Juárez, 2018), due to the increasing diversity and population of predatory species.

6.2 Minimization of threats to soil functions

Table 152. Soil threats

Soil threats	
Nutrient imbalance and cycles	Leaving crop residues on the soil surface as stubble increases soil organic reserves and the content of elements useful for plant nutrition (Báez-Pérez *et al.*, 2017).
Soil salinization and alkalinization	Buffers the risk of alkalinization and reduces this constrain in the medium term (Báez-Pérez *et al.*, 2017).
Soil contamination / pollution	Given the reduction of tillage practices during the production process, fossil fuel consumption is also reduced. In the medium term, as the soil organic reserves are increased, the reduction of fertilizer application rate is feasible and the accumulation of SOC, and emissions of greenhouse gases to the atmosphere are reduced (Cotler *et al.*, 2016).
Soil biodiversity loss	Annual addition of crop residues to soil surface conserves more moisture and enhances biodiversity (Báez-Pérez *et al.*, 2012b; Mena-Covarrubias *et al.*, 2016).
Soil compaction	Worm population and other soil organisms resulting from the large availability of organic matter favors macro-porosity and then soil compaction (Cotler *et al.*, 2016). The superficial layer of crop residues protects the soil surface against drops from rainfall avoiding crust formation (Verhulst, François and Govaerts, 2015).
Soil water management	This production system allows greater usage of available water for crops. The permanent layer of crop residues has the capability to retain soil moisture in the profile (Báez-Pérez *et al.*, 2012b).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Average grain yield over the last 16 years of irrigated summer maize or sorghum and winter wheat or barley in Guanjuato is shown in Table 153(SIAP, 2020). However, returns under conservation agriculture or conventional agriculture are higher than 17 t/ha for maize, up to 12.5 t/ha for sorghum, 9 t/ha for wheat and 7 t/ha for barley (Báez-Pérez *et al.* 2012a; Báez-Pérez *et al.* 2012b; Báez-Pérez and González-Torres 2018; Báez-Pérez and González-Torres 2020).

Table 153. Average state production of irrigated corn, sorghum, wheat and barley in the state of Guanajuato, Mexico

Year	Maize	Sorgum	Wheat	Barley
	t/ha			
2004	7.8	8.6	6.0	5.7
2005	8.5	8.6	6.1	5.9
2006	7.2	7.9	5.9	5.7
2007	8.2	8.5	6.2	5.6
2008	8.5	8.4	5.8	5.7
2009	7.5	8.3	6.4	5.6
2010	8.2	8.6	6.7	6.0
2011	7.9	8.7	7.0	6.2
2012	8.6	9.0	6.7	5.9
2013	8.5	8.9	3.4	3.4
2014	8.8	8.9	6.1	5.6
2015	8.9	5.9	5.1	5.6
2016	8.9	7.8	6.8	6.2
2017	8.9	7.9	6.8	5.9
2018	8.6	7.8	6.9	6.0
2019	9.3	7.2	6.8	6.0

6.4 Mitigation of and adaptation to climate change

The buildup of a layer of crop residues on the soil surface in conservation agriculture implies a gradual accumulation of SOC, mainly from 0 to 5 cm depth, however, at greater depths the accumulation of this element is lesser.

6.5 Socio-economic benefits

The adoption of conservation agriculture practices for the production of cereals by farmers implies greater profitability due to less investment for the preparation of the soil and greater production as compared to the traditional production system. A benefit-cost ratio that can be achieved, as estimated by Báez-Pérez and González-Torres (2018) and Báez-Pérez and González-Torres (2020) is 2.5 for corn, 2.0 for sorghum, 2.3 for wheat and 2.1 for barley.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 154. Soil threats

Soil threats	
Nutrient imbalance and cycles	Studies are needed to adjust fertilization rates for cereal production under conservation agriculture systems over the long term. The SOC increase must be accompanied with more rational use of agrochemicals too.
Soil salinization and alkalinization	The application of agricultural gypsum can be used as temporal alternative to correct soils alkalinity.
Soil contamination / pollution	Frequent use of herbicides to control narrow-leaf weeds in sorghum crops (i.e. glyphosate) implies a high risk of soil contamination.

7.2 Increases in greenhouse gas emissions

The estimated CO_2 emission from conservation agricultural systems is 2.24 g $CO_2/m^2/hr$ and 1.5 g $CO_2/m^2/hr$ from conventional tillage practices (Báez-Pérez *et al.*, 2019). This difference is due to the lower content of soil organic matter under conventional systems. N_2O emissions in conventional production systems with high doses of nitrogen fertilization (400 units per hectare) are 30 g/ha/day, with peaks of more than 300 g/ha/day. In conservation agriculture systems with the same level of fertilization, emissions may also be higher due to the greater amount of decomposing organic matter. Methane emissions have not been studied yet. Nitrous oxide emissions in this type of soil in agricultural systems are about 30 g/ha/day due to N fertilizer rates (up to 400 units of N per ha from urea) for corn production.

7.3 Conflict with other practice(s)

Crop residues can promote weed development, interfere with the flow of irrigation water, and cause denitrification due to excess moisture during the rainy season. For this reason, the use of herbicides, remarking of the cultivation furrows and attending to leveling practices have been necessary.

7.4 Decreases in production (Food/fuel/feed/timber/fibre

If constraints related to weed pressure and irrigation management are expected, it is possible to have economic losses that move farmers away from conservation agriculture.

7.5 Other conflicts

Another limitation of conservation agriculture is the access to suitable and affordable machinery such as precision planters.

8. Recommendations before implementing the practice

The implementation of double row beds (1.6 m) for corn and sorghum, and double or triple row beds for wheat or barley, has been very successful in the Bajío. The implement known as ″V″ rake allows discover the edges of the beds and improve use of the bare soil, which increases the success of germination and the best distribution of stubble across on the soil surface.

9. Potential barriers for adoption

Table 155. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	It is easy to implement conservation systems on flat soils; on sloped soils it is necessary to implement additional practices such as terracing, live walls or contour crops.
Cultural	Yes	Landowners are often elderly people accustomed to farming on weed-free land. For this reason, in conservation tillage fields, they view crop residues as simple garbage.

Barrier	YES/NO	
Social	Yes	Farmers practicing conservation agriculture are generally smallholders, and therefore, they face difficulties organizing farmers´ groups to request government support such as permanent technical assistance.
Economic	Yes	The purchase, or rental of agricultural implements, for agricultural conservation works has a high cost.
Institutional	Yes	In Mexico there is a program to support agriculture with national scope (PROCAMPO), but this is insufficient because its operating rules do not directly stimulate productive diversification or support for the more expensive processes of conservation systems.
Legal (Right to soil)	Yes	The delivery of property titles to community producers has significantly increased the sale of productive lands and the formation of new large estates, in which there is no conservationist vision but of maximum intensity.
Knowledge	Yes	Further training of technicians is required, as well as better research and demonstration platforms to properly establish conservation practices.
Natural resource	No	Vertisols are found in the most favorable areas for agricultural land use.

Photos

Photo 73. Wheat over corn stubble, Agro-technological Field "Xonotli", Villagrán, Guanajuato, Mexico. Autumn-winter cycle 2017-2018

Photo 74. Corn over wheat and corn residues. Agro-technological Field "Xonotli", Villagrán, Guanajuato, Mexico. Autumn-winter cycle 2017-2018

Photo 75. Corn over wheat and corn residues (left) and Corn over wheat residues (right)

Photo 76. Corn on deteriorated Vertisol

Photo 77. Corn in traditional agriculture on Vertisol

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38. Rehabilitation of hardened neo-volcanic soils in Mexico

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1. Practice(s) used

Crop rotations, Manure applications, Intercropping

2. Description of the case study

Tepetates (rocky beds) are indurated layers of volcanic tuffs exposed on the soil-like surface after intense erosion processes. *Tepetates* cover 11.6 percent of the Mexican territory (232 000 km^2; Guerrero-Eufracio, Luna and Caballero, 1992), corresponding 30 000 km^2 to the Neovolcanic Axis (Zebrowski, 1992). These volcanic materials are classified in Mexico according to the succession of volcanic ash deposits (according to the successive age of deposition: t1, t2, t3, etc.), in addition to the presence or absence of calcium carbonates, or silica as cementing material (Quantin *et al.*, 1993) and the corresponding hardness (fragipan or duripan *tepetates*). Fragipan *tepetates* are relatively easy to break mechanically (with heavy machinery), transforming them into an arable substrate, useful for agriculture or reforestation; however, they are deficient in soil organic carbon (SOC), nitrogen, and phosphorus. The broken substrate is initially composed of inert fragments of *tepetate*, but after adding organic manures and/or fertilizers, and adopted cropping systems or reforesting, soil aggregates are gradually formed, where SOC is accumulated (Báez-Pérez *et al.*, 2007a). The conversion of an inert substrate into fertile soils is based on the formation and stabilization of aggregates, which allow the improvement of the soil structure and of the concomitant physical, chemical, and biological soil properties. Báez Pérez *et al.* (2002) evaluated the content of SOC in several agricultural production systems and concluded that the accumulation rate of this element, during the first four years of cultivation, was 2.2 to 4.4 tC/ha/yr, depending upon the agronomic management implemented. Huge additions of organic fertilizers are added mainly crop residues and manure in the cultivable layer (0 to 20 cm deep). SOC accumulation declines later to a lower rate but the accumulation is more tenuous. According to the highest values of SOC found in different cropping systems, it was determined that these subtracts can store in the first 20 cm depth more than 88 tC/ha after 20 years of cultivation. According to Báez-Pérez *et al.* (2009) CO_2 emissions were estimated, on average, 20 kgCO_2-C/ha/yr and SOC loss due to water erosion up to 60 kgC/ha/yr. It is important to consider that a lot of manures and organic residues are added during the first years and later years of soil improvement and the emissions can become high.

3. Context of the case study

One study location is in the Valley of México watershed, in the middle part of the northwestern slope of the *Sierra Nevada* mountains of the state of México, between 18° 54′ 39′′ to 19° 33′ 00′′ north latitude and 98° 31′ 11′′ to 98° 48′ 10′′ West longitude, and covers the Estado de Mexico, Morelos, Puebla y Tlaxcala in the central part of the Central Volcanic Belt (Figure 37). The altitude of the zone is 2 300 to 2 900 m.a.s.l. The climate of the piedmonts corresponds to warm temperate moist, but it changes with the altitude (e.g. in *Sierra Nevada* Mountains).

Other selected site is in Santiago Tlalpan (Photo 78), municipality of Hueyotlipan (Tlaxcala, Mexico), in the eastern part of the piedmont of the *Sierra Nevada* mountains. The climate is also warm temperate moist; according to the Köppen classification corresponds to temperate sub-humid, C(w2)(w)g(i0) (García, 2004). The average annual temperature is 14.8 °C and the annual precipitation is 769 mm/yr, concentrated mainly in the summer (June–September). According Werner (1992), 54 percent of the State of Tlaxcala is in danger of becoming an area of *tepetates* because of the erosion of the Cambisols and Andisols developed down the slopes and valleys.

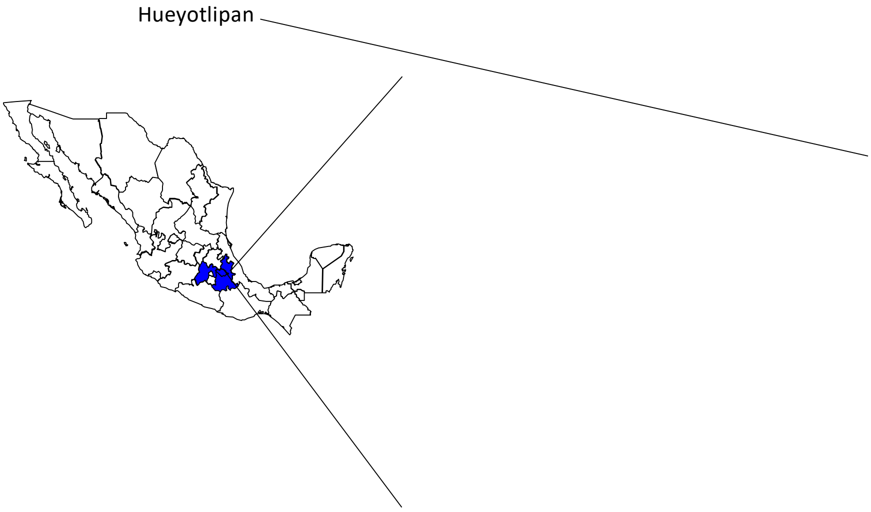

Figure 37. Study area:

Source: Aurelio Báez Pérez, Jorge D. Etchevers Barra, Claudia I. Hidalgo Moreno, Christian Prat, Angélica Bautista Cruz, Juan Fernando Gallardo Lancho

4. Possibility of scaling up

Results can be scaled within the space of the Transversal Neo-volcanic Axis (volcanic chain located between the *Sierra Madre Occidental* and the *Sierra Madre Oriental*, extending from the islands Revillagigedo (in the Pacific Ocean, West) to the Gulf of Mexico (East), following the parallel 19, crossing Mexico City and the states of Nayarit, Jalisco, Colima, Michoacán, Guanajuato, Querétaro, Mexico, Hidalgo, Morelos, Tlaxcala, Puebla, and Veracruz (Region of *Los Tuxtlas*).

5. Impact on soil organic carbon stocks

Tepetates habilitated for agricultural production or forestry, after processes of breakage and formation of terraces, only contain traces of SOC; then, the SOC baseline of these substrates is near zero and hence their high potential for C sequestration. As indicated, according to studies on the accumulation of this element (Báez Pérez *et al.,* 2002), the SOC-sequestration potential is 88 tC/ha over 20 years of cultivation based on persistent income of organic manures. In rainfed production systems (maize monoculture), with removal of harvest residues, the SOC content does not reach beyond 5 mgC/g (11 tC/ha), even after 50 years of cropping (Table 156); this could be verified in old plots that were hand-broken with pick and shovel in the past and interviews directed to farmers of the region. SOC accumulation in habilitated *tepetates* for agricultural production occurs linearly during the first few years (2.2 to 4.4 tC/ha), and then increases very slowly (logarithmic model). Large additions of organic waste or fertilizers were added, more than 8 tons of dry matter (ha/yr); based on the above, these figures are not so high. Subsequently, organic additions decrease and with the development of the soil, their mineralization increases, decreasing the net rate.

Table 156. Evolution of SOC stocks in the study sites of the Sierra Nevada mountains of the state of México

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Treatments and more information	Reference
0.01	0.22	50	Monocrop of maize with harvest-residues removal.	Báez-Pérez *et al.* (2002)
	0.36	60	Rotation or association of maize + legumes (broad bean or bean)	
	0.48	50*	Corn in rotation with persistent application of organic manures. *the soil can accumulate carbon by 50 years more.	
	8.8	10	Intensive production in greenhouse with irrigation and constant application of organic manures.	

Climate is Temperate sub-humid, C(w2)(w)g(i0) according to the Köppen classification and soils are Durisol eutric epipetric

Baseline value of C stock

Considering that the newly ruptured substrate contains only traces of SOC, the baseline is close to zero; Covaleda *et al.* (2007) indicated that the baseline of *tepetates* ranges from 2 to 10 tC/ha.

Duration

It was estimated that the accumulation of SOC in rainfed cultured *tepetates*, for the first 20 cm of soil depth, depends on the growing system, namely: a) Monocrop of maize (*Zea mays*) with harvest-residues removal, 5 mgC/g (11 tC/ha) even after 50 years of cultivation; b) Rotation or association of maize+legumes (broad bean or bean) up to 10 mgC/kg (22 tC/ha) even after 60 years of cultivation; c) corn in rotation with persistent application of organic manures 22 mgC/kg (48 tC/ha) after 100 years; and d) Intensive production in greenhouse with irrigation and constant application of organic manures, up to 40 mgC/g (88 tC/ha) in just one decade of cultivation (Báez-Pérez *et al.*, 2002).

6. Other benefits of the practice

6.1. Improvement of soil properties

Physical properties

Breakage of the indurated substrate favors water infiltration, aeration, aggregate formation, and moisture retention (Báez *et al.*, 2007b). According to Prat, Chaparro-Ordaz and Rugama (2003) hydraulic conductivity prior to the mechanical breakage of the fragipan *tepetate* is 0.45 cm/h and after agricultural rehabilitation can reach 6 cm/h.

Physical and chemical properties

The soil pH decreases from slightly alkaline to slightly acidic after 20 years of cultivation (Covaleda *et al.*, 2009).

Biochemical properties

The conversion of *tepetate* to arable soil gradually favors the accumulation of SOC and, consequently, the biochemical characteristics improves.

Biological properties

Biological activity increases significantly, especially by arbuscular mycorrhiza fungi, producing glomalin, which contributes to the SOC sequestration (between 15 and 30 percent of such C is recalcitrant; Báez-Pérez *et al.*, 2010; Báez-Pérez *et al.*, 2012). Biological activity in *tepetates* has a favorable response to the incorporation of manures, green manures, and crop residues derived from the polyculture maize-bean-broad bean association (Alvarez-Solís, Ferrera-Cerrato and Etchevers-Barra, 2000). Exposure of *tepetate* outcrops means soil erosion and loss of biodiversity; then, the habilitation of *tepetates* for agricultural or forestry production enhances soil biodiversity.

6.2 Minimization of threats to soil functions

Table 157. Soil threats

Soil threats	
Soil erosion	Habilitation of *tepetates* for agricultural purposes and conservation and leveling works significantly limits erosion; according to Prat *et al.* (1997) and Báez-Pérez *et al.* (2009), who measured soil mass and suspended sediments transported by runoff waters, a primary *tepetate* loses annually 20 t/ha/yr of sediments, in contrast to the broken *tepetate* with continuous incorporation of organic manures, having only losses of 2 t/ha/yr.
Nutrient imbalance and cycles	The content of these items increases as organic reserves increases. Main initial deficiencies are N and P (which can be alleviated with fertilizers). Báez Pérez *et al.* (2002) reported about 5 mg/kg of soil available P in a maize system with harvest residues removal even after 50 years of cultivation; but this available P increases to 60 mg/kg if organic manures are continuous applied after 100 years of cultivation.
Soil acidification	The soil pH decreases from slightly alkaline to slightly acidic after 20 years of cultivation (Covaleda *et al.*, 2009).
Soil biodiversity loss	Exposure of tepetate outcrops means soil erosion and loss of biodiversity; then, the habilitation of tepetates for agricultural or forestry production enhances soil biodiversity (Prat *et al.*, 2015).
Soil pore sealing (Crusting of the soil surface)	When the tillage is not appropriated, the new habilitated *tepetate* presents crusting on soil surfaces problems due to the lack of an adequate physical structure (Báez Pérez *et al.*, 2007a); hence, water infiltration can be limited, affecting negatively the germination of small seeds (such as wheat); a large addition of organic manures and the introduction of widespread cover crops gradually improve the soil structure.
Soil compaction	The primary *tepetate* substrate has a high bulk density (about 1.6 t/m^3); after mechanical rupture and agricultural rehabilitation the bulk density dropped to 1.1 t/m^3 (Peña and Zebrowski, 1992; Prat *et al.*, 2002).
Soil water management	*Tepetates* are located on piedmonts, with slopes ranging from soft to medium; for this reason, construction of terraces at contours, contour lines, borders, or living walls are highly recommended and crucial for reducing the erosive power of rains (or facilitating the management of irrigation waters, where available) (Prat *et al.*, 2015).

6.3 On provision services

In habilitated *tepetates* for agricultural production, under rain-feed conditions, Báez *et al.* (1997) obtained 3.5 t/ha of barley and maize; in crop association of maize+bean+broad bean, they got 3.6, 0,12, and 2.0 t/ha, respectively.

6.4 Mitigation of and adaptation to climate change

Tepetates habilitated for agricultural and forestry production constitute a sinkhole of SOC, as explained above. According to Báez-Pérez *et al.* (2009), CO_2 emissions in rain-feed agricultural systems ranged, on average, from 5 to 10 kgCO_2-C/ha/h during the wettest months (May to September) and about 1 kgCO_2-C/ha/h during the dry season.

6.5 Socio-economic benefits

The habilitation of *tepetates* involve new farmlands for the livelihood of communities, living close to poverty. According to Prat *et al.* (1997b), most farmers fail to reach the equivalent to the minimum income that, that is profits covers only half the value of the basic basket of a Mexican family (on average) in rural communities located in Mexico's Transverse Neo-volcanic Axis, as well as in large areas of the Andean region; different names equivalent to *tepetates* are used in other countries of Central and South America (Gardi *et al.*, 2014), as *talpetates*, *cangahuas*, or *trumaos*.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 158. Soil threats

Soil threats	
Soil contamination / pollution	Some gullies of erosion in tepetate areas are used for garbage dumps and urban-waste landfills, polluting waters and rivers downstream; therefore, they can only be rehabilitated for forest use.
Soil biodiversity loss	Immoderate (often illegal) logging in Mexico causes land clearing inside forests, favoring accelerated soil erosion and the appearance of outcrops of tepetates, which are highly erodible. In severe cases the formation of gullies drives to badlands, denoting a serious deterioration of the environment.

Soil threats	
Soil water management	In the past, land conservation works, small dams, and reservoirs were performed in these areas of tepetates, in addition to reforestation with eucalyptus trees, to control the runoffs of the upper areas, for the protection of the most populated lowlands.

7.2 Increases in greenhouse gas emissions

CO_2 emissions increase when the soil moisture increases, giving peaks of up to 25 kg/ha/h.

7.3 Decreases in production (Food/fuel/feed/timber/fibre

After the process of breakage, *tepetates* have high risk of erosion, and the first results of crop production are not satisfactory if suitable practices of soil conservation and crop selection are not considered. Take note that the production obtained in the first year of cultivation is often very low; the most common designated crop is maize.

8. Recommendations before implementing the practice

Breakage of *tepetates* to, at least, 45 cm deep is recommended. This process was carried out with Caterpillar tractors (D7 or D8), equipped with two chisels or rippers (Zabrowski and Sánchez, 1997). This work realized on substrates provides quite rough structure; hereafter a plow is required for softening the surface of the terrain. The shape and slope of the land generally determine the design of the plot for future agricultural works. The final slope of the habilitated *tepetate* should allow a maximum soil infiltration of the rainwater and reduce runoff in case of excess of it. It has been demonstrated that an efficient way to perform the breakage of the *tepetate* substrates is to make a first step with the heavy machinery in a linear direction, with spacing of 30 cm between the lines penetrated by the chisels, and then perform a second step, but this time perpendicular to the first, as if a grid were marked. Introduction of symbiotic bacteria is advisable previous to sowing leguminous species.

9. Potential barriers for adoption

Table 159. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	There are large areas where erosion has formed deep gullies; with such a degree of deterioration, the process of habilitating *tepetates* is no longer possible.
Social	Yes	The rates of migration from rural to urban areas are very high (even to United States of America), due to the lack of opportunities as agricultural producers; one of the consequences is that the remaining older people are the dominant sector that works the land.
Economic	Yes	The process of breaking and habilitation of *tepetates* for agricultural or forestry production is expensive; however, it would be suitable if government supports or implements programs of land rehabilitation to combat irreversible soil losses (Zabrowski and Sánchez, 1997).
Institutional	Yes	More institutional efforts are desirable to lead public policies focused in preventing and reversing soil degradation.

Source: (Zebrowski, 1992)

Photos

All photos by: © Aurelio Báez Pérez

Photo 78. Top: Plots of tepetates freshly broken and conditioned for agricultural production (Tlapan, Tlaxcala, Mexico)

The same site cultivated two and three years later with corn and beans. Bottom from left: Tepetate resulting as consequence of soil erosion (Tlaxcala, Mexico); severe erosion of tepetates with formation of gullies (Calzada del Mamut, Tlaxcala); and tepetate fragment of and a soil aggregate after several years of cultivation of a rehabilitated tepetate (Tlapan, Tlaxcala). Photographs from authors

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Photo 79. Heavy machinery breaking

Photo 80. Terrace formation

Photo 81. Tepetate plot conditioned for cultivation

Photo 82. Cultivated tepetate plot

Photo 83. Cultivated tepetate plot

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39. Crop-pasture rotation on black soils of Uruguay and Argentine

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1. Related practices and hot-spot

Integrated crop-livestock systems, no-till; Black soils

2. Description

Experience with crop-pasture rotations (CPR) in Uruguay and Argentine "black soils" is based on long-term experiments and its adoption by farmers (Studdert, Echevarria and Casanovas, 1997; Díaz-Zorita, Duarte and Grove, 2002; García-Préchac *et al.*, 2004; García-Préchac *et al.*, in press). If conventional tillage (CT) is used in continuous cropping (CC), tolerable erosion rates are not feasible and crop residues decomposition rate is high. Both processes lead to soil organic carbon (SOC) content reduction and soil degradation. No-till (NT) reduces erosion and residues decomposition, but is not enough to avoid degradation if the predominant crop is soybean, leaving low residues amount with low C/N rate (Beretta-Blanco *et al.* 2019); the opposite is true in case that the rotation crops are only grasses like wheat and corn (Díaz-Zorita, Duarte and Grove, 2002; Novelli, Caviglia and Melchiori, 2011; Salvo, Hernández and Ernst, 2010). Since soybean (*Glycine max*) is the crop of higher value and demand globally, the first approach to avoid soil degradation is to use only NT, and double crop with wheat (*Triticum aestivum*) or barley (*Hordeum vulgare*) or cover crops in winter, and to rotate in summer soybean with corn (*Zea mays*) or sorghum (*Sorghum bicolor*). This could be enough in soils with low erosion risk and high SOC content. But for the majority of the black soils is better to rotate some years of NT cropping with some years of grass and legume pastures for direct grazing (Studdert *et al.*, 1997; Studdert and Echevarría, 2000; García-Préchac *et al.*, 2004). During the pasture duration erosion is almost eliminated and SOC increases because a great deal of the pasture net photosynthesis produces the root system, leaving its residues into the soil. This improves nitrogen availability, soil structure, soil biomass and biodiversity, determining higher productivity. Experimental data demonstrate that NT-CPR assures SOC content maintenance over time if the initial value is high; if it is low due to degradation, SOC sequestration is a longer term process (Salvo, Hernández and Ernst, 2010).

3. Context of the case study

Geographical location: Río de la Plata Grasslands, or Bioma Pampa, in Argentine, Uruguay and South Brazil, between latitudes 30 ^{0}S and 40 ^{0}S.

The region is temperate, with precipitation from 500 mm in the West to 1 600 mm in the East; according with IPCC the climate is Warm Temperate Dry in the West and Warm Temperate Moist in the East.

Soils are black soils (Mollisols and Vertisols with mollic surface horizon or Phaeozems and Chernozems, Durán *et al.*, 2011). They have original high SOC content, but under CC they have lost a significant proportion.

SOC stock (1 m depth) of Pampean soils in Argentine accounted for 4.22 ± 0.14 Gt in an area of 48.2 Mha: 101 t/ha in uncropped controls, over 90 t/ha in pastures, 86 t/ha in cropped field, and 70 t/ha in flooded sites. Agricultural use led to a reduction of SOC by 16 percent in the upper 50 cm, and by 9 percent at 50–100 cm depth. Land use influenced the SOC sequestered in soil, but not its allocation in depth (Berhongaray *et al.* 2013).

Uruguayan soils have a mean SOC content of 13.4 kg/m^3 (1 m depth), that is 17 percent over the world mean content; Uruguayan Mollisols and Vertisols have between 15 and 20 kg C/m^3, with 40-50 percent located in the upper 20 cm (Durán, 1998). The soil testing laboratory of INIA-Uruguay analyzed over 1 000 samples a year sent by farmers. During the 13 years from 2002 to 2014, the average SOC content of the samples decreased by 20 percent (Beretta-Blanco *et al.*, 2019). The majority of these samples came from the dominant soil use and management system in the period: NT CC with soybean all the summers.

Therefore, in the case of the black soils of our region, the conservation of their present SOC content is an overarching task.

The main use of these soils is cropping, being the most important wheat, barley and oats (*Avena spp.*) in winter, soybean and corn in summer.

4. Possibility of scaling up

Crop-pasture rotations had been very important soil use and management systems in Argentine, and predominant in Uruguay, before the overwhelming global soybean demand and high price from the beginning of the present century, resulting in predominance of CC and reduction of CPR. In Uruguay, CPR still occupy almost 40 percent of the present cropped area, because this soil use system allows farmers to accomplish the soil conservation official regulations in soils with erosion risk (see section 8, Institutional). Recently, the area under CPR is recovering due to the reduction of soybean grain price since 2014 and the high value and demand achieved by beef.

The cropped area in the region, mainly on black soils, is relatively less than the area under grazing, where other soils are predominant; the region has very important animal production with beef the most important product, but also dairy and sheep production are very relevant. Therefore, there is the opportunity to use productive seeded pastures of grasses and legumes in mixed systems, rotating with crops.

The CPRs could be used in any place of the world with black soils, in which the farm size and the combined existence of cropping and animal production, able to use pastures, exists.

5. Impact on soil organic carbon stocks

All the referenced information indicates that the stabilization of SOC content is immediately possible using CPR with NT. The increase of SOC when black soils are degraded takes longer periods. Salvo, Hernández and Ernst (2010) report that in a Typic Argiudoll with 30 percent less SOC content in the upper 18 cm than the pristine soil, after with 10 years of experiment comparing CC and CPR, both with NT, CPR had more humified C (C-MAOM) content in the upper horizon. The following table presents the results of long-term experiments (Table 160).

Table 160. Evolution of SOC stocks in crop-pasture rotations long-term experiments in Uruguay and Argentina

Location	Soil type	Baseline[a] C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	Depth (cm)	More information	Reference
Uruguay	Typic Argiudoll, Silty Clay Loam	42.9	0.4	35	0-20	The first 28 years under CT, the following 7 years under reduced tillage	Baethgen (2003)
Uruguay	Typic Argiudoll, Silty Clay Loam	31.2[b]	0.24[b]	48	0-15	The first 28 years under CT, the next 18 years under reduced tillage and the last 2 years under NT.	Quincke *et al.*, (2012), cited by García Préchac *et al.* (2017)
Argentine	Typic Argiudoll, Loam	78.1[b]	0.31[b]	10	0-20	CC and CPR, both with CT	Studdert *et al.* (1997)
Uruguay	Typic Argiudoll, Silty Clay Loam	44.7	0.21	10	0-18	CC with CT and RCP with NT	Salvo, Hernández and Ernst (2010)
Uruguay	Abruptic Argiudoll, Silty Loam	27.3	0.41	20	0-15	CC and RCP, both with NT	Rovira *et al.* (2020)

aCC, the business as usual practice, was taken as the Baseline reference in all the cases. bEstimated from the published data. For all references, associated climate is warm temperate moist

6. Other benefits of the practice

6.1. Improvement of soil properties

Physical properties

e.g. water infiltration, soil aggregates, and bulk density, improve with SOC increase and deteriorate with SOC decrease. Accordingly, experimental data show that they are better in CPR than in CC, and with NT than with CT (García-Préchac *et al.*, 2004; García-Préchac *et al.*, in press).

Chemical properties

e.g. pH, and CEC, are positively affected by higher SOC content in NT CPR. More soil organic matter determines higher CEC and cation retention in the CEC positions that equilibrates with higher base cations concentration in the soil solution, tending to keep pH higher and close to neutrality (Beretta-Blanco *et al.*, 2019).

Biological properties:

e.g. biological activity and biodiversity, are positively affected by higher SOC content. A research work in one of the Uruguayan long-term experiments determined that soil macro biodiversity in NT CPR was not different of the one in the pristine soil under natural grassland (Zerbino-Bardier, 2005).

6.2 Minimization of threats to soil functions

Table 161. Soil threats

Soil threats	
Soil erosion	Under NT CPR, similar to natural grassland, and significantly less than under NT CC (García-Préchac *et al.*, 2004)
Nutrient imbalance and cycles	Higher availability, particularly N, in NT CPR than CT CPR and NT CC (García-Préchac *et al.*, 2004, and in press)
Soil contamination / pollution	In CPR, the use of agrochemicals and fossil fuels is reduced as compared with CC, in direct proportion to the time and space occupied by the pastures (García-Préchac *et al.*, 2004, and in press)
Soil acidification	Higher SOC determines higher CEC, higher base cation in the CEC positions and higher pH of the soil solution (Beretta-Blanco *et al.* 2019).
Soil biodiversity loss	Conserved in NT CPR (Zerbino-Bardier, 2005).

Soil threats	
Soil compaction	During pastures grazing in the CPR, livestock density must be controlled to avoid soil surface compaction by animal trampling, particularly under wet soil condition. Nevertheless, this overcompaction can be managed without using mechanical tillage if there is enough time of fallow in NT between the total herbicide application to end the pasture and the planting of the first crop of the following cropping part of the rotation (García-Préchac *et al.*, 2004). This time should be over one month to allow pasture root decomposition and to give the opportunity for soil drying and wetting by evaporation and rain, respectively, generating shrinking and swelling. In integrated crop-pasture systems, topsoil compaction can be minimized or prevented with controlled agricultural machinery transit and avoiding excessive grazing of crop residues in winter (Alvarez *et al.* 2014; Fernández, Álvarez and Taboada, 2015). Topsoil deterioration by integrated management was insignificant. Rather than compaction, the increase in topsoil resistance is likely to be due to a process of topsoil hardening (Fernández, Álvarez and Taboada , 2011).
Soil water management	Improved bulk density and macroporosity determines better water infiltration in the soil (García-Préchac *et al.*, 2004, and in press)

6.3 Increases in production (e.g. food/fuel/feed/timber)

With CT, crop productivity is significantly higher in CPR than in CC. With NT this difference depends on the amount and permanence of residues left during the used crop rotation; if soybeans are the summer crop the difference exists, but not if corn or sorghum are the summer crops (García-Préchac *et al.*, 2004, and in press). An example is shown in the following Figure 38.

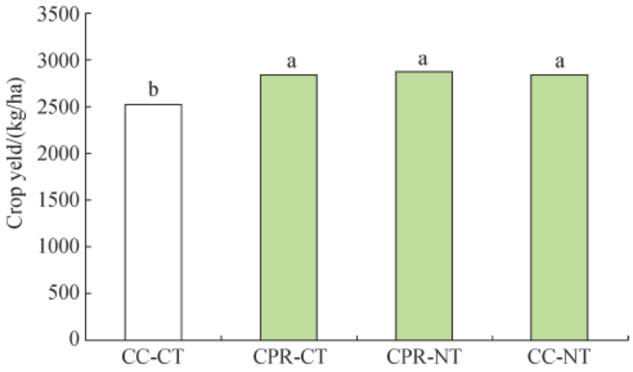

Figure 38. Means of 7 wheat crops yields between 1994 and 2008, in the treatments of a long-term experiment which started in 1993 on a Typic Argiudoll

Bars with the same letter are not significantly different (Ernst and Siri-Prieto, 2009)

Shifting crop-pasture rotations to continuous no till farming in hundreds of farms during 4 years was found to deteriorate soil properties and decrease wheat yields in Uruguay (Ernst *et al.* 2018).

6.4 Mitigation of and adaptation to climate change

In terms of mitigation, NT CPR keeps high SOC content, avoiding its loss to the atmosphere, more details are given in 7.2.

In terms of adaptation, CPR is more diverse production system than CC. CPR includes animal and vegetable productions, with variations inside each one of the phases of the rotation. Therefore, a diverse system is much more resilient to climate change, in the short term (drought, water excess) and in the long term (increased temperature and rain variability).

6.5 Socio-economic benefits

A more diverse system is more resilient to changes in the prices of products and production inputs, and its economical result is less variable in the middle and long term. Also, the physical productivity of the system is less variable between years with different climate conditions. This is more evident if more diverse crops are included, and even more if it adds a component of animal production, like in the CPR. An economic study performed in 1990 with the production data set of a long-term experiment between 1963 and 1989, with prices of products and inputs at the 1990 US Dollar (USD) value, calculated that the mean gross income was 260 USD/ha in CT CPR vs. 154 USD/ha in CT CC, due to lower use of fuel and N fertilizer and higher crop yields, plus the addition of the animal production in the CPR; the inter-annual gross income coefficient of variation was 73 percent in CPR vs. 95 percent in CC, indicating that the economic result of CPR is more stable in the long term (Fernandez, 1992, cited by García-Préchac *et al.*, 2004). An unpublished similar economical study (Fernández and Andregnette, 2004, cited by García-Préchac, 2008), comparing different CC NT rotations vs. 3 years crops-3 years pastures rotation with NT, concluded that the differences in gross income were in favor of the CC with soybeans in all the summers (USD 240 vs. USD 220 in the CPR); CC rotations alternating corn with soybean had a little lower gross income (USD 208). The inter-annual coefficient of variation of the gross income was again smaller in CPR (23 percent) than in the average of the CC cases (34 percent).

The main use of agrochemicals and fossil fuels is during cropping phase, and are almost nil during the pasture phase of the CPR. Therefore, the use of agrochemicals and fuel is reduced in CPR compared with CC, in direct proportion to the time and space occupied by the pastures (García-Préchac *et al.*, 2004, and in press).

Also, the CPR create a mosaic in the landscape, with areas under different crops together with areas under grazed pastures. This gives much more opportunity to wild animal life, in particular, to pollinators.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 162. Soil threats

Soil threats	
Soil compaction	Consider here what was described in 6.2, and the following. Some work was focused on cattle grazing impacts of winter crop residues on soil properties (no till farming) during the cropping phase of rotations (Fernández, Álvarez and Taboada, 2011, Álvarez *et al.* 2014; Franzluebbers, Sawchik and Taboada, 2014, Peyroud, Taboada and Delaby 2014, Fernández, Álvarez and Taboada, 2015). Interestingly, rather than cattle grazing impacts, crop (maize and soybean) mechanical harvesting affected more severely topsoil physical properties in these integrated crop livestock systems.

7.2 Increases in greenhouse gas emissions

In the previous sections, the benefit of NT CPR over other practices was indicated in maintaining or increasing SOC content, therefore avoiding C loss to the atmosphere.

An experimental comparison of soil N_2O emission in the field (three years) from CPR or CC, factorially combined with CT and NT, could not find significant differences (Perdomo, Irisarri and Ernst, 2009; Salvo, 2014). In the same experiment, CH_4 emission in the field during two years found no differences between the treatments, and in all them there was net absorption in the soil of this gas (Salvo, 2014).

7.3 Conflict with other practice(s)

Global market conditions, like disproportionately unbalanced prices and demand for some products (as was the soybean case from the beginning of the XXI century to 2014) make farmers to simplify the production system, generating CC instead of CPR, and monoculture in the CC. All the experimental information shows that CC with monoculture leads to soil degradation (being SOC content reduction the main indicator), loss of productivity and other environmental problems.

7.4 Decreases in production (Food/fuel/feed/timber/fibre

See 6.3, above.

8. Potential barriers for adoption

Table 163. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Depending on soil texture and SOC content, the necessary duration of pasture in the rotation is 2 to 4 years (García-Préchac *et al.*, 2017; García-Préchac *et al.*, in press); the heavier the texture and the higher the SOC content, the longer the needed time under pastures.
Economic	Yes	See 7.3.
Institutional	Yes	Lack of active soil conservation policies is a barrier for the adoption of diverse systems like the CPR. Conversely, its existence, like in Uruguay, help to counterbalance the problem discussed in "Economic". The regulation mandates to have a Soil Use and Management Plan that as evaluated by the USLE/RUSLE model will produce annual soil erosion rate below the Tolerance rate officially established for the predominant soil in the planned area (Pérez Bidegain *et al.*, 2018).
Legal (Right to soil)	Yes	Land property allows farmers to plan soil use and management on mid and long-term. Farmers that rent the land are tied to immediate results, making them follow the market signals.

Visual representation of the practice


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Photo 84. After between 2 to 4 years, crops move to the pasture paddocks and pastures move to the cropped plots

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40. Mitigation of SOC losses due to the conversion of dry forests to pastures in the plains of Venezuela

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1. Related practices

Improved pasture management; Grassland

2. Description of the case study

Over the past two decades, twenty of every one hundred hectares of semi-deciduous forests in Venezuela have been deforested and converted to pastures (Hansen *et al.*, 2020). This conversion generally implies a notable loss of biodiversity and a profound change in the activity and composition of soil microbial communities. One way to mitigate this impact is to encourage rational ranching in the lowest positions in the basin. Various measurements of SOC obtained at different depths and seasonal periods in deep alluvial soils with high clay content of western Venezuela, where the semi-deciduous forests, with moderate degradation (*Cecropia peltata* L.) (Photo 85), were converted to pastures (African Bermudagrass: *Cynodonnlemfuensis* Vanderyst) (Photo 86, Photo 87), show a stability in the total weight of fine roots (with a diameter less than 2 mm) and a slight increase in the original weight of soil humus, especially in the 10 to 20 cm depth interval. This result is related to a good extensive livestock system based on crop rotation practices and adequate paddock loading with minimal soil disturbance. For example, in this area the original forest had been cut down manually and burnt, and the pastures have never been fertilized, but have been mowed annually to control weeds and to promote grass growth. Additionally, species from the original forest that could not be cut by hand, as well as vegetation of secondary growth, like palms and some species of legumes, were observed in the pasture. Cattle was introduced into young pastures (5 years old) to graze during the dry season and in the early and late rainy season (approximately 100 animals in an area of 103 hectares). The cattle remained in this pasture until they consumed all the available grass. In the old pastures (18 years old), cattle (50-100 animals) was introduced every 1–2 months and remained for 3–7 days, while consuming all the available grass.

The moderate increase in SOC in young pastures is attributed to carbon inputs from the roots of the native vegetation, the constant regeneration of secondary vegetation, new contributions of aboveground and belowground biomass from grasslands and by the retention of organic matter in the clay fraction with the highest activity (CEC greater than 24 meq per 100 g of clay) (Photo 86). The stability in the SOC content in old pastures is mainly attributed to the increase in microbial activity and the stability in the weight of the dry biomass generated by the grassland (Photo 87) (González-Pedraza and Dezzeo, 2011, 2014a, 2014b, 2020). In young pastures $C\text{-}CO_2$ was affected by soil humidity conditions along the year and the lowest $C\text{-}CO_2$ value can indicate lower efficiency of microorganisms to decompose the organic matter (González-Pedraza and Dezzeo, 2014a).

3. Context of the case study

This is a regional case applicable to the colluvial-alluvial plains of the Western Plains of Venezuela, with semi-deciduous forest vegetation developed on relatively fertile, partially floodable clay soils with poor drainage, a life zone of tropical dry forest and sub-humid mesoclimate, pastures are dominant land cover and livestock use.

4. Possibility of scaling up

This case can be scaled to other regions of the world with dry forests under the same geomorphological and hydrometeorological conditions.

5. Impact on soil organic carbon stocks

According to Table 164, the value 3.49 is above the mean. It is important to note that these are clay soils on geoforms of deep alluvial accumulation, so the increase occurs in the first 5 years, immediately after the loss of carbon due to felling and burning of the previous vegetation. In this sense the value (3.49) will begin to fall significantly, as the saturation point is reached, as has happened in the second case (0.67).

Table 164. Evolution of the SOC stocks in two experimental sites (pastures of different ages) between 2004 and 2009 and 1991 and 2009 at 0-40 cm depth in the western plains of Venezuela

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration(Year)	More information	Reference
51.8 (b)	3.49	5	Two experimental sites in the same landscape, with the same soil, at the same depth, but with different management. Evaluation of the results in both cases was carried out in 2009. In the first case, 5 years of management was evaluated (2004 to 2009) and in the second case, 18 years was evaluated (1991 to 2009). In both cases, the most significant carbon increase was observed in the 10 to 20 cm depth. The baseline magnitude comes from laboratory analysis carried out on the soil with the original conditions of tree cover and exclusively forest use.	(a) Rodríguez *et al.* (2015); (b) González-Pedraza and Dezzeo (2014a)
	0.67	18		

Source: Rodriguez et al. (2015)

Climate is sub-humid mesoclimate, and soil type is PellicVerticol (mazic)

6. Other benefits of the practice

6.1. Improvement of soil properties

There is a slight increase in the total nitrogen content of 0.06 Tg/ha/yr (in pastures of 5 years old) and 0.11 Tg/ha/yr, in 18 years old pastures, with respect to the soils that still retain their dominant forest cover.

There are no variations in the total mass of fine roots which contributes to stability of soil structure and soil permeability.

A slight increase in soil moisture content is observed in the first 20 cm depth for 5-year-old pastures.

There is a significant decrease in the percentage of mineralized total carbon (TEC / SOC) under young pastures, with a subsequent long-term stabilization of the same indicator for mature *Cynodon* pastures.

In contrast, a greater increase in the water-soluble carbon content (SCW) of young grasslands is observed during the dry period of the year (January-April).

6.2 Minimization of threats to soil functions

Table 165. Soil threats

Soil threats	
Soil erosion	There are no losses affected by soil erosion due to the position of the study sites corresponding to geo-forms with deep alluvial accumulation. The processes of transport of soil material in the micro-relief are compensated with new contributions within the alluvial-fluvial system as a whole.
Nutrient imbalance and cycles	Through this practice, stability and balance is achieved in the total mass of fine roots and in the content of nutrients (phosphorus, calcium, magnesium) in the first 20 cm depth, between forest soils and soils converted to pastures after a period of 5- and 18-year-old.
Soil salinization and alkalinization	There is not salinization or alkalization in these soils.
Soil contamination/pollution	There is no use of herbicides but use of a roller with a blade and a rotary for weed control.
Soil acidification	There are no significant changes in the soil acidity between forest (average pH 6.0) and young and old pastures (average pH 5.6 and 6.0 respectively).
Soil biodiversity loss	The microbial ratio of organic carbon in the first 5 cm of the soil (MIC / SOC) remains stable in old pastures during the dry season, while under forest and young pastures there is a significant decrease of soil biodiversity.
Soil compaction	There are no changes in soil bulk density due to type of land cover/land use. The reported mean values were 1.1 and 1.2 g/cm3 at the depth of 0-20 cm for pastures and forest, respectively, with slight increases to 1.4 at the depth of 30-40 cm in other land use types.
Soil water management	There are no conflicts of use in the study site due to any pressure with the availability or use of water. There are also no risks of contamination of aquifers due to the use of pesticides, salinity or excessive evapotranspiration. The water catchment comes from nearby canals and underground sources.

6.3 Mitigation of and adaptation to climate change

This practice provides GHG mitigation in sites that have been deforested and converted to pastures, since it allows the possible medium and long term CO_2 sequestration in the soil. See more details in section 7.2.

7. Tradeoffs with other threats to soil functions

Table 166. Soil threats

Soil threats	
Soil biodiversity loss	When forests are slashed and burned to be converted to pastures, consequent changes in humidity and average temperature negatively affect biological activity and respiration rates. It is observed that in the first 5 cm of depth, young pastures have a much lower metabolic ratio (qCO2) than forests, which may indicate a lower quality and availability of carbon for microbial activity.
Soil compaction	There could be significant increase in soil compaction if management does not apply pasture rotation frequency and load animals properly.
Soil water management	There are no conflicts of use in the study site due to any pressure with the availability or use of water. There are also no risks of contamination of aquifers due to the use of pesticides, salinity or excessive evapotranspiration. The water catchment comes from nearby canals and underground sources. There is no systematic management of the water resource as such.

8. Recommendations before implementing the practice.

Cynodon nlemfuensis does not resist long term high intensity grazing, therefore, overgrazing should be avoided.

9. Potential barriers for adoption

Table 167. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Producers do not have the capacity to solve flooding problems on pastures.
Cultural	Yes	Lack of management of forage resources, which results in overgrazing, undergrazing and weed expansion as a consequence of inadequate management of animal load, pasture subdivisions and fertilization.
Social	Yes	It is not a difficult task to try to sensitize the sector for the adoption of management strategies. However, greater association is required between producers.
Economic	Yes	The extensive livestock system is constant or cover crops using mechanization, which could have a greater impact on the physical soil properties due to agricultural machinery usage, but also on chemical soil properties due extended use of chemical fertilizers and pesticides.
Institutional	Yes	The Venezuelan government has generally overcome the reductionist or sectoralist approach. However, so far it is not very challenging task to sensitize the transformation sector to achieve a balance in the prices of livestock products, which put additional pressure on current land use.
Legal (Right to soil)	Yes	Lack of land ownership of recent agrarian colonization by producers who are not being subject of agrarian reform, have to submit to the rescue of public lands, in accordance with the Land and Agrarian Development Law (LTDA).
Knowledge	Yes	With the exception of genetic crossings and the introduction of improved pastures, the extensive livestock system remains on the margins of technological innovations.

Photos


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Photo 85. Pasture with 18-years-old in the in Western Llanos of Barinas State, Obispos municipality, Venezuela


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Photo 86. Tropical semi-deciduousforests in Western Llanos of Barinas State, Obispos municipality, Venezuela


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Photo 87. Pasture with 5-years-old in the in Western Llanos of Barinas State, Obispos municipality, Venezuela

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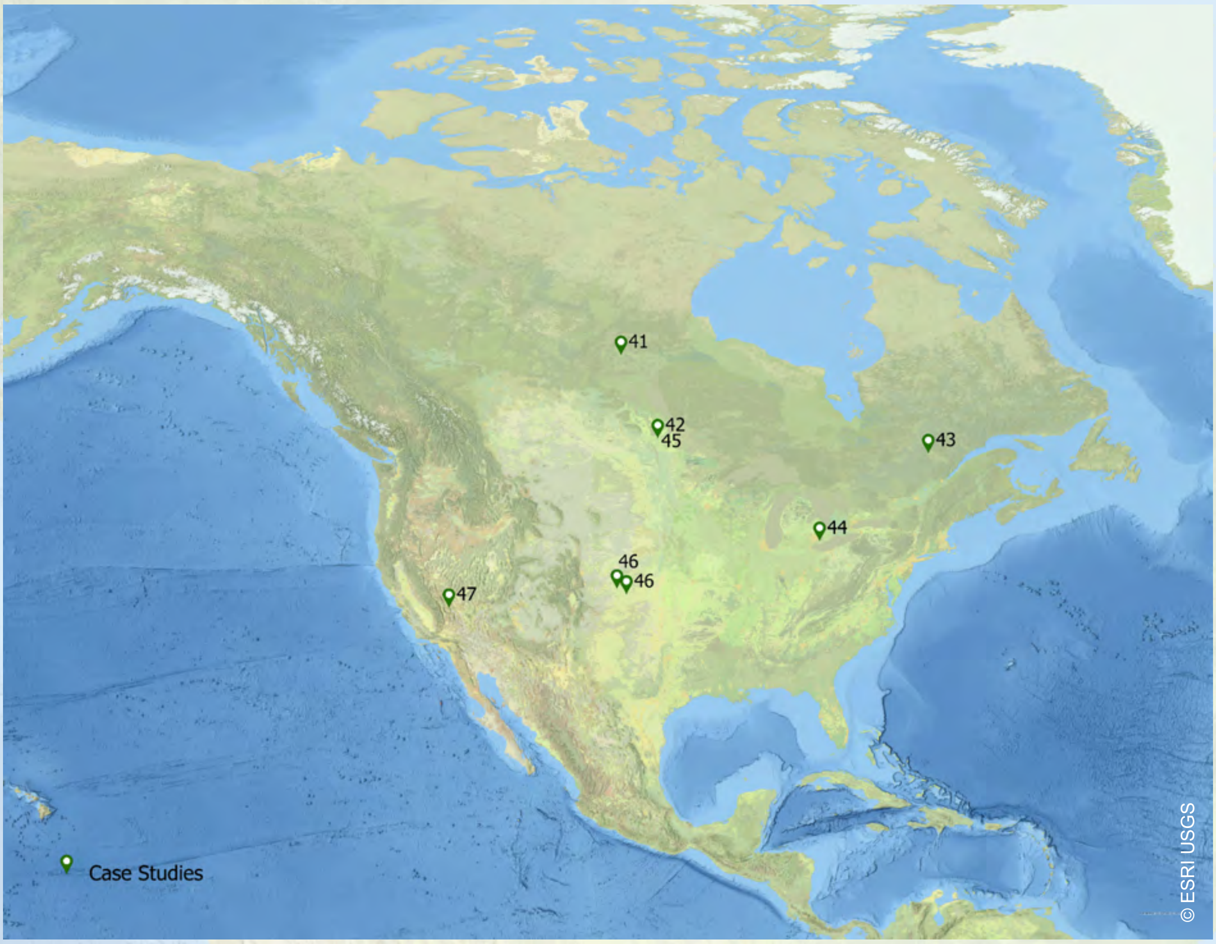
North America



Case Study ID	Region	Title	Practice 1	Practice 2	Practice 3	Duration
41	North America	Biochar as a soil amendment for carbon sequestration in Canada	Biochar	Manure	Chemical fertilization	1 to 3
42	North America	Willow riparian buffer systems for biomass production in the black aoils of Elie, Manitoba, Canada	Biochar	Manure	Chemical fertilization	1 to 3
43	North America	Response of soil carbon to various combinations of management practices (annual-perennial rotation system, animal manure application, reduced tillage) in Quebec, Canada	Reduced tillage	Mulching	Crop rotation	21
44	North America	Zone tillage of a clay loam in Southwestern Ontario, Canada	Zone tillage	No-till		13 to 16
45	North America	Long-term no-tillage maize in Kentucky, the United States of America				
46	North America	Deficit irrigation scenarios using sprinkle irrigation system in Western Kansas, the United States of America	No-till	Irrigation	Deficit irrigation	5 and 8
47	North America	Whole orchard recycling as a practice to build soil organic carbon in the San Joaquin Valley, California, the United States of America	Mulching			9

41. Biochar as a soil amendment for carbon sequestration in Canada

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1. Related practices

Biochar, manure applications, mineral fertilization, integrated soil fertility management

2. Description of the case study

Biochar has been used for thousands of years in the Amazon, and to date most of the research on biochar as an agricultural soil amendment concerned tropical soil. However, amending intensively managed temperate soils with biochar is a more recent approach to Canadian agriculture. Canadian field studies on how biochar impacts soil properties are mostly concentrated in Newfoundland & Labrador and Quebec (Table 168). This case study focuses on the impact of biochar on SOC and other soil chemical, physical and biological properties at the east-west and north-south field-scale across Canada. It consists of a replicated field trial established with biochar as a soil amendment combined with poultry manure or poultry manure and N fertilizer in southern Ontario **(this case study)**. This study was unique because of its location on a farm and managed under commercial farming operations. It was the largest longer-term commercial farming-based biochar field trial (with appropriate statistical design and replication), and demonstration site in Ontario focusing on soil health, C sequestration, greenhouse gas emissions and climate change resilience. A concurrent study on agricultural producer's knowledge of biochar and its adoption and an economic analysis was also conducted. This study was unique because all management operations at the field-scale were implemented so that they could be easily scaled-up to commercial farming operations in southern Ontario and/or regions with a similar soil type and climate. This allowed producers interested in commercial biochar application to use standard operating procedures, eliminating the need for additional or special equipment.

Table 168. Summary of field-scale studies across Canada that have evaluated the impact of biochar as an agricultural soil amendment

Location (Soil Type)	Biochar Feedstock	Experimental Details	Biochar Application Rate (t/ha)	Study Results
Newfoundland & Labrador (sandy)[1]	Sugar maple-yellow birch	Sugar beet	15	Biochar significantly increased crop yield; biochar enhanced macro- and micro-nutrient uptake by crop
Newfoundland & Labrador (loamy sand)[2]	Sugar maple-yellow birch	Sugar beet	0, 10, 20, 40 & 80	Biochar had positive effects on soil hydrological properties, especially at a 40 t/ha application rate
Quebec (loamy sand)[3]	Pine wood chips	Maize, soybean & switchgrass	0, 10 & 20	Biochar addition did not significantly increase SOC for all crops
Quebec (sandy clay loam)[3]	Pine wood chips	Maize, soybean & switchgrass	0, 10 & 20	SOC increased significantly under maize and switchgrass
Quebec Namur (sandy loam)[4]	Maple-oak-birch	Maize	1 + 170 kg/ha UAN	No significant increase in SOC. Significantly greater maize biomass; significantly greater N use efficiency Note: biochar was preconditioned with urea ammonium nitrate (UAN) to decrease application rates (c.f. Dil *et al.*, 2014)
Ontario[5]	Spruce-pine	Maize-soybean	3	SOC increased significantly under maize in the first year of application but then decreased sharply by 3rd year

[1]Abedin and Unc (2020); [2]Altdorff *et al.* (2019); [3]Backer *et al.* (2016); [4]Dil (2011); [5]Mechler *et al.*, 2018

3. Context of the case study

The study site was located in Bayfield (43°34′45.8′N, 81°39′52.2″W), Ontario, Canada on a commercial poultry-cash crop farm, situated 183 m above sea level with a slope of 1.5 percent. The soil was classified as a uniform grey-brown Luvisol with a loam texture. The 30 year mean weather data was obtained from a nearby weather station located in Goderich (43°74′28′N, 81°71′39″W), Ontario, Canada, which recorded a mean annual temperature of 8 °C and an annual precipitation of 991 mm. Commercial farming practices included the production of maize (*Zea mays* L.) in rotation with soybean (*Glycine max* (L.) Merr.). Poultry manure, based on switchgrass (*Panicum virgatum* L.) bedding, was added on a 3-year rotation at a rate of 6 t/ha and was topped-off with urea N fertilizer at 135 kg N/ha only in the years maize was produced. The site was tilled using a disc harrow and weeds were controlled by N-phosphonomethyl glycine (Glyphosate).

The experimental design was a randomized complete design with three replications (Figure 39). The treatments were: 6 t/ha poultry manure plus 135 kg N/ha N fertilizer (MN); 3 t/ha poultry manure plus 3 t/ha biochar (MB); and 3 t/ha poultry manure, 135 kg/ha N fertilizer and 3 t/ha biochar (MNB). The plot size for each treatment replicate was 10 m × 10 m, with a 3 m border between plots. Biochar in MB and MNB treatments was added using a drop spreader and worked into the soil using a Salford RTS vertical tillage unit to ensure uniform distribution. Commercial farm management operations including herbicide additions and N fertilizer application rates were standard agronomic practices for this region of southern Canada. The biochar was added to the respective treatment replicates only once over the duration of this study. Sample collection began in May and terminated in November of each year. The biochar was provided by Titan Carbon Smart Technologies (Saskatoon, Saskatchewan, Canada). The feedstock of the biochar was a 50/50 mix of pine (*Pinus* spp.) and spruce (*Picea* spp.), and the resultant biochar was produced using slow pyrolysis (550 °C, 15 min). Biochar chemical and physical properties are described in detail in Mechler *et al.* (2018).

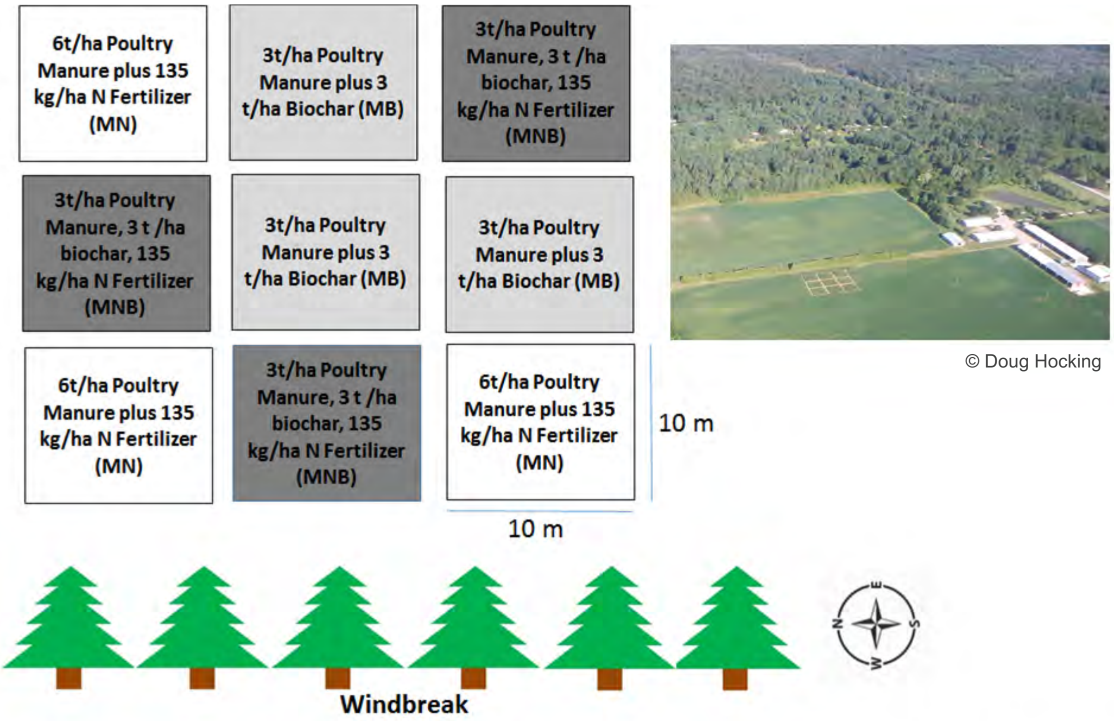

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Figure 39. Complete randomized design of field-scale commercial farming operations in southern Ontario

4. Possibility of scaling up

This case study can be scaled-up to other regions if soil texture, climate, and the type of biochar (c.f. Mechler *et al.*, 2018) are the same.

5. Impact on soil organic carbon stocks

On the loam textured Luvisol in southern Canada, the addition of biochar plus poultry manure (MB treatment) in the first year of the study led to a 117 percent increase in SOC, whereas adding biochar plus poultry manure and N fertilizer (MNB treatment) increased SOC by 33 percent. However, 3 years after adding biochar SOC was 5 percent and 12 percent greater in the MB and MNB treatments, respectively. The control treatment without biochar (MN) showed no change (year 1) or a 3 percent loss (year 3) of SOC (Table 169). Increasing SOC in biochar treatments may be explained by the carbon input due to the biochar itself, as plant production has not changed.

Dil and Oelbermann (2014) simulated the effect of biochar addition on soil organic C stocks over 150 years in Ontario using coarse and medium textured soil. They found that a one-time application of maple-oak-birch derived biochar at 2 t/ha and preconditioned with urea ammonium nitrate led to a greater increase and long-term stabilization of SOC. They also found that the quantity of C stabilized was influenced by soil texture. Soil texture also determined if the C was stabilized in the active, slow, or passive C fractions.

Table 169. Change in SOC stocks in a grey-brown Luvisol (loam texture) in the moist, cool temperate climate of southern Canada

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (years)	Depth (cm)	Amendment application
15.6	0	1	10	3 t/ha poultry manure & 150 kg/ha N fertilizer
15.6	-2.6	3	10	3 t/ha poultry manure & 150 kg/ha N fertilizer
13.2	15.4	1	10	3 t/ha poultry manure and 3 t/ha biochar
13.2	0.7	3	10	3 t/ha poultry manure and 3 t/ha biochar
11.7	3.9	1	10	3 t/ha poultry manure & 150 kg/ha N fertilizer
11.7	1.4	3	10	3 t/ha poultry manure & 150 kg/ha N fertilizer

Source: Mechler et al. (2018); Mechler (2018); Jiang, (2019)

This when soil was amended with poultry manure and nitrogen fertilizer, poultry manure and biochar, or poultry manure, nitrogen fertilizer and biochar in year 1 and 3 under a maize crop

6. Other benefits of the practice

6.1. Improvement of soil properties

The following soil properties are improvement when biochar was added to temperate soil in southern Canada (Mechler *et al.*, 2018; Mechler, 2018; Jiang, 2019). Increases/decreases are significant at $p<0.05$ in treatments with biochar (MB and/or MNB):

- Increased water infiltration
- decreased bulk density
- increased water stable aggregates (> 250µm)
- decreased soil water content
- moderation of soil temperature extremes: maintenance of soil temperature under warmer than usual growing season. May provide greater resilience under projected climate change.
- maintenance of soil pH
- increased ammonium, decreased nitrate, decreased phosphorus
- increased soil microbial biomass carbon
- increased number of macrofauna
- changes in microbial community composition and substrate utilization
- increased mycorrhizal fungal colonization

6.2 Minimization of threats to soil functions

Table 170. Soil threats

Soil threats	
Nutrient imbalance and cycles	Nitrate and phosphorus adsorbed to biochar decreasing the leaching of these nutrients to ground and surface waters. Adsorption of these nutrients has not affected crop productivity.
Soil acidification	Maintenance of soil pH. Southern Ontario soil is calcareous but can tend towards acidity from heavy N fertilizer input. Biochar can moderate acidification from N fertilizer use.
Soil biodiversity loss	Biochar changes the composition and the carbon sources utilized by a more active microbial community. Biochar also provides habitat for micro and macro fauna.
Soil compaction	Decreases soil bulk density, increases water infiltration, and increases water stable aggregates.
Soil water management	Decreases soil water content. This did not affect crop yield, even in a drier than normal growing season.

Source: Mechler et al. (2018); Mechler (2018); Jiang, (2019)

6.3 Increases in production (e.g. food/fuel/feed/timber)

Adding biochar to temperate agricultural soil is a relatively new concept and results from longer-term field studies when biochar is combined with poultry manure are still limited. However, results from this case study showed that adding biochar when combined with poultry manure or with poultry manure and mineral N fertilizer caused no negative effects on SOC sequestration, soil health or crop productivity relative to commercial farming practices using poultry manure and mineral N fertilizer as a soil amendment. It was observed that during a drier than average growing season, treatments amended with biochar exhibited a greater resilience which was exhibited by an increased productivity in maize root and shoots.

6.4 Mitigation of and adaptation to climate change

The goal of this case study was to determine the impact of biochar on soil health and greenhouse gas emissions using conventional agroecosystem management practices. However, life-cycle assessment (LCA) is necessary to determine the actual impact of greenhouse gas emissions and carbon sequestration starting with biochar generation to its final use as a soil amendment.

To test for climate change adaptation potential, a macrocosm study, where soil collected from the three field treatments and seeded with soybean was exposed to single (ambient, elevated temperature or elevated CO_2) or multifactor (elevated temperature and CO_2), was conducted to evaluate the impact of climate change on soil amended with and without biochar. The response to climate effects on soil and soybean properties were substantially greater compared to that of amendment types. The absence of interactive effects indicated that soil amended with biochar functioned independently of single or multicomponent climate effects. Soil microbial biomass C and N, a short-term indicator for changes in land management, showed that amendment type MNB led to a lower SMB-C. However, the microbial biomass was not affected by climate effects, but climate effects influenced the way C and N were accessed by microbes in all amendment types, shifting the species richness and diversity, and the structure of the microbial community (Jiang, Galo and Oelbermann, 2021).

6.5 Socio-economic benefits

Regional or local biochar generation from regionally or locally sourced feedstocks enhances rural economics by providing job opportunities if high-quality biochar application becomes economically viable. Assuming a cost of $2 800 per t (in 2018) of high-quality biochar (Titan Carbon Smart Technologies), it is currently not economically viable for field application, even when considering a reduction in N fertilizer application, carbon credits, and generous yield increases. Despite the currently high cost, prices are expected to decline to $300/tonne (Garcia-Perez, 2017 pers. comm.) with an increase in the number of high quality biochar producers and the available supply over time will make the addition of biochar more economically realistic (Figure 40 and Figure 41).

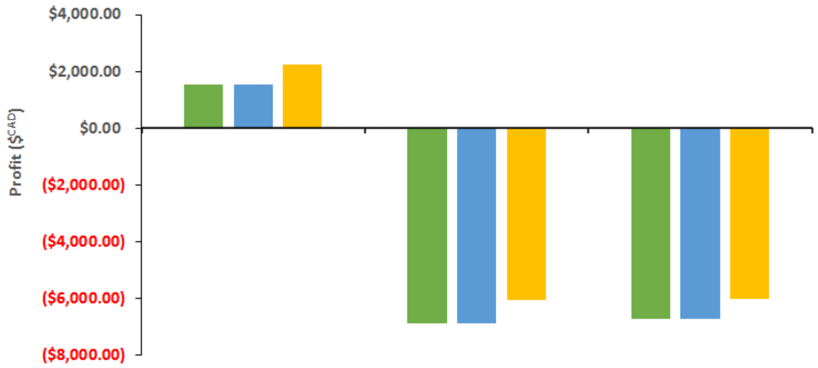
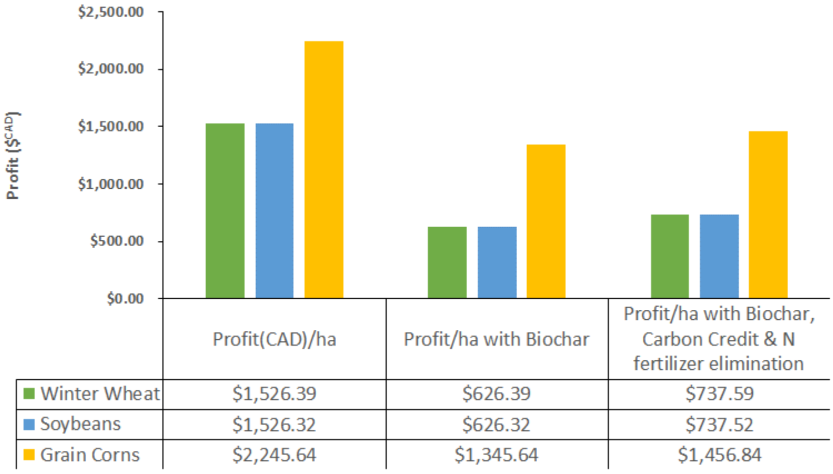


Figure 40. Economic analysis of biochar as a soil amendment at $2,800/t in southern Ontario, Canada. Data provided by M.Suta



	Profit(CAD)/ha	Profit/ha with Biochar	Profit/ha with Biochar, Carbon Credit & N fertilizer elimination
🟩 Winter Wheat	$1,526.39	$626.39	$737.59
🟦 Soybeans	$1,526.32	$626.32	$737.52
🟨 Grain Corns	$2,245.64	$1,345.64	$1,456.84

Figure 41. Economic analysis of biochar as a soil amendment at $300/t in southern Ontario, Canada. Data provided by M.Suta

The present case study showed that cost was the leading factor when considering the addition of biochar to agricultural soils, followed by a lack of research, unknown/confirmed benefits of biochar as a soil amendment and the need for a distinct economic benefit (Figure 42 and Figure 43). Because of this, farmers are wary of investing in anything without applicable and convincing research that show positive economic results. The economic analysis quantified the viability of biochar application using yield statistics from the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) for winter wheat, soybeans, and grain corn, and fertilizer pricing from Syngenta Canada, and carbon pricing from the government of Ontario's proposed cap and trade program.

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Figure 42. Word cloud of agricultural producer's perception of biochar as an agricultural soil amendment in southern Ontario, Canada

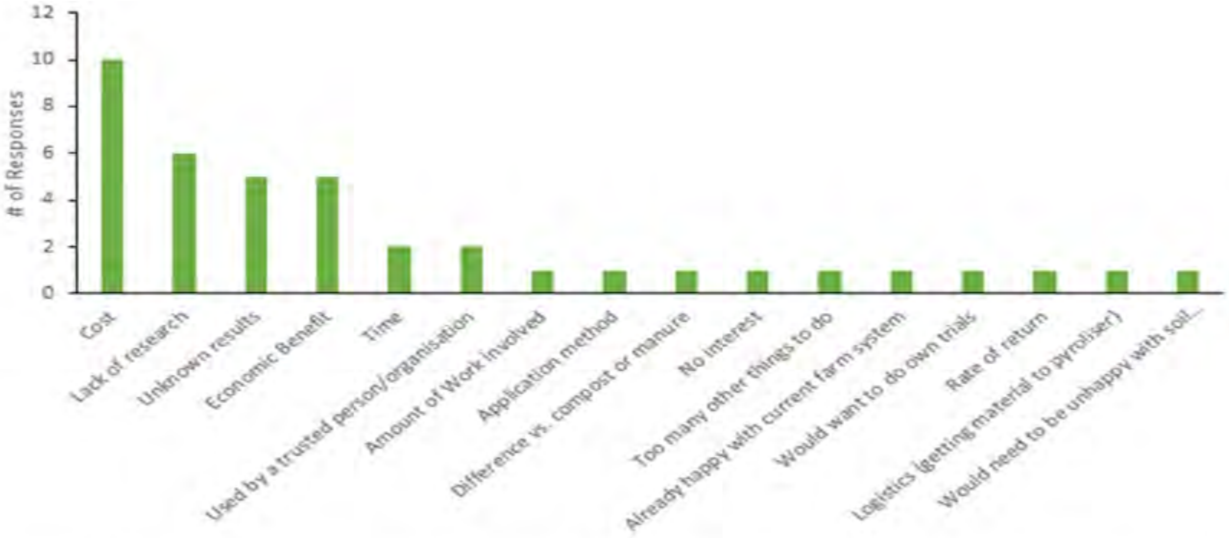

Figure 43. Factors affecting agricultural producers' willingness to apply biochar on their fields in southern Ontario, Canada. Data provided by M.Suta

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 171. Soil threats

Soil threats	
Soil water management	Soil water content is frequently lowered in biochar amended soil. It did not impact crop productivity.

7.2 Increases in greenhouse gas emissions

Mean greenhouse gas emissions over 3 field seasons were not statistically different among treatments with and without biochar

Table 172. Mean greenhouse gas emissions for treatments with and without biochar over 3 field seasons

	MN	MB	MNB
CO2 (mg CO2-C /m/h)	127	118	122
N2O (µg N2O-N/m/h)	74	68	72

MN: 6 t/ha poultry manure plus 135 kg N/ha fertilizer; MB: 3 t/ha poultry manure plus 3 t/ha biochar; MNB: 3 t/ha poultry manure, 135 kg N/ha fertilizer plus 3 t/ha biochar

7.3 Decreases in production (Food/fuel/feed/timber/fibre

Crop productivity was not negatively affected in treatments with or without biochar.

8. Recommendations before implementing the practice

It is necessary to ensure addition of a high-quality biochar. This includes the use of a high-quality feedstock. Feedstock containing heavy metals (e.g. lead, zinc, arsenic) and other contaminants will generate a low-quality biochar containing heavy metals, polycyclic aromatic hydrocarbons and dioxins, which will negatively affect the soil, plants and environment. Therefore, it is important to use biochar produced from high quality feedstock and through a consistent pyrolysis process. Adding biochar without other amendments will increase carbon but may compromise crop productivity. Additionally, the performance and stability of biochar in soil is dependent on soil type, plant/crop species, and climate. Growers interested in using biochar on their property should apply it to a small area of their farm and then monitor results in subsequent years.

9. Potential barriers for adoption

Table 173. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	No	Biochar improves soil biophysical characteristics (Lehmann and Josef, 2015).
Cultural	No	Biochar has been used for thousands of years in tropical and temperate environments (Lehmann and Josef, 2015).
Economic	Yes	Biochar is currently expensive and research on the most effective application rate is not yet confirmed (Suta, 2018, pers. comm.).
Institutional	Yes	In Canada, before applying biochar it must be approved by the Canadian Food Inspection Agency. Biochar must be of high quality and not contain contaminants.
Knowledge	Yes	Most agricultural producers do not have an understanding of what biochar is and its effect on soil (Suta, 2018, pers. comm.).
Natural resource	Yes	High quality feedstock may be limited in certain regions. Biochar production currently occurs at low capacity therefore increasing its price. Production at higher capacity will reduce its price to $300/t (Garcia-Perez, 2017, pers. comm.).

Photos

Photo 88. Spruce-pine biochar used in this case-study and applied at 3 t/ha in the first year of the field study

Photo 89. Biochar field-scale trials

Biochar field-scale trials in southern Ontario (A + B) under a maize crop in 2017; (C) maize crop with six-month-old biochar; (D) biochar 15 months after its addition under a soybean crop; (E) greenhouse gas measurements in early autumn 2017 under a maize crop; (F) biochar field-scale trial in southern Ontario shortly before maize harvest

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42. Willow riparian buffer systems for biomass production in the black soils of Elie, Manitoba, Canada

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1. Related practices and hot-spots

Riparian Buffers; Black soils

2. Description of the case study

The case study was conducted in the La Salle Watershed North-West of Elie in the Red River region of southern Manitoba, Canada (Figure 44). The objective of the study was to examine the effects of willow cutting planting density on biomass yield, soil organic carbon sequestration, nutrient runoff mitigation, and biodiversity enhancement using three intra-row planting densities. The willow riparian buffer was planted using *Salix dasyclados* cultivar "India" in a replicated block design using three intra-row spacing treatments: 0.5 m – single row; 1.0 m – single row; 0.75 m – double row Swedish design; and a control grass plot in the Spring of 2013 (Figure 45; Photo 90 and Photo 91). Baseline soil sampling was completed in August of 2013. Soil samples were collected at depths of 0-15 cm, 15-30 cm, and 30-45 cm at a distance of 0.5 m away from the willow buffer planting.

Biometric data was collected on an annual basis in late fall (late October or early November) after senescence: the number of whips/stool, the basal diameter of the largest whip in each stool and the height of the tallest whip in each stool for each of the ten willow stools. Wildlife diversity was recorded using trail cameras installed on the site (Photo 92). Harvesting of willow biomass was completed in 2016 and 2019 in early November by coppicing at approximately three inches above the root collar (Photo 93 and Photo 94). Wet and dry biomass weights were collected to determine the total biomass from each of the field rows, mid-row, and riparian row in the sub-plot of each treatment. All the biomass outside of the sub-plots were removed from the plot and chipped.

In this case study, we are focused on soil organic carbon sequestration and present data from the single row 1.0 m spacing planting treatment only.

Figure 44. Physical location map of case study site (Latitude: 49°57'29''N, Longitude: 97°55'17''W). Inset-map of Canada with blue dot showing geographical location of Elie, Manitoba.

Source: Google Earth and J. Blair English, Fardausi Akhter, Raju Soolanayakanahally, Laura Poppy, Henry de Gooijer, Daniella Giardetti, Rhonda Thiessen, Chris Stefner

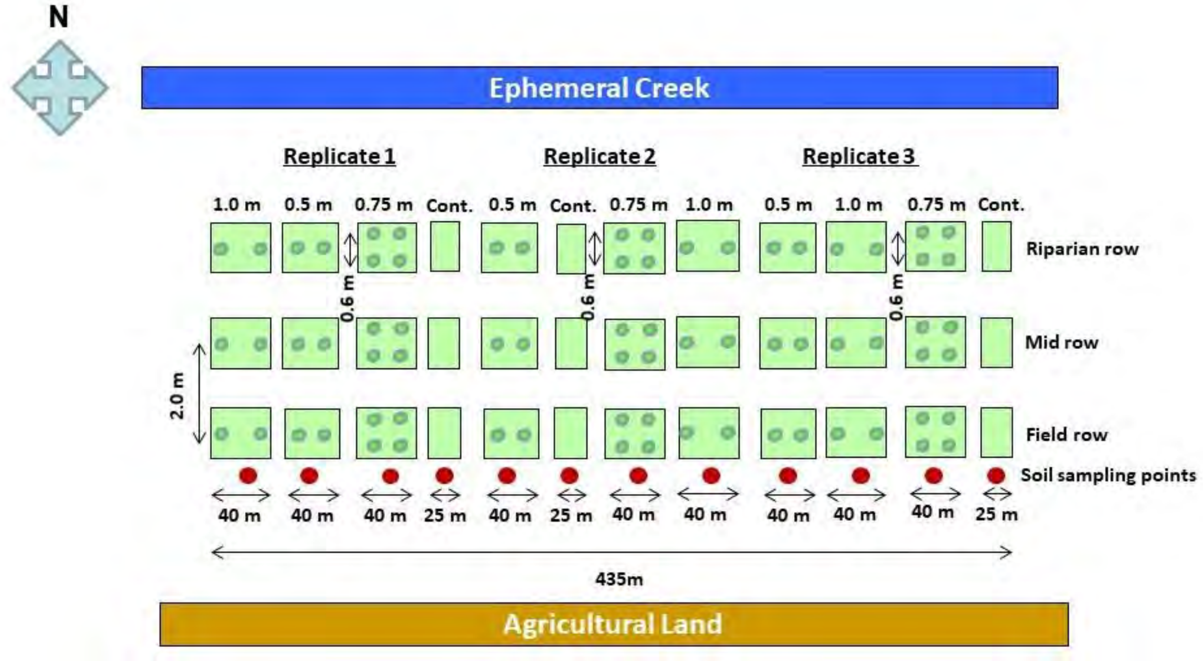

Figure 45. Willow riparian buffer system design layout

3. Context of the case study

Geographic Location: LaSalle Watershed North-West of Elie in the Red River region of southern Manitoba.

Pedo-climatic context: Morris soils in the Canadian System of Soil Classification are described as imperfectly drained Gleyed Solonetzic Black Chernozemic soils (Soil Classification Working Group, 1998; Manitoba Soil Series Descriptions (MAFRI, 2010) developed on moderately to strongly calcareous fine-textured lacustrine deposits.

Climate: A sub-humid continental climate in the eastern prairie region of western Canada (Powell, 1978).

Land-use: Dryland annual cropping of mixed grains, oilseeds, soybeans and corn.

Coverage of the case study: Local.

4. Possibility of scaling up

The number of options for edge of field technologies, such as willow riparian buffers, is limited but growing could be scaled up and applied in different geographic areas and climatic conditions. Willow riparian buffers can be used to intercept agrochemicals (above ground drift) and nutrient run-off, create wildlife habitat, and generate revenues from biomass for energy production (Hénault-Ethier *et al.*, 2019). The system can be particularly suitable for marginal lands, jurisdictions with legislated wetland buffers, or areas that cannot be farmed and, therefore, would otherwise not generate income for the farmer. Willow riparian buffer could also be adapted to meet the different site-specific needs of the landowners. For example, the system can stabilize eroding banks or shorelines of adjacent water bodies in a crop field and provide physical separation of agricultural activities from sensitive aquatic areas.

Salix spp. (willow) is a commonly grown species for short-rotation biomass production (3-year harvest cycle). The species responds well to coppicing, is an early successional species with rapid growth and high resprouting capacity (Wilkinson *et al.*, 2007). Recent breeding advances have allowed for more productive, faster-growing, better adapted willow with higher resistance to insects, disease, and environmental conditions (Huang *et al.*, 2020).

5. Impact on soil organic carbon stocks

Baseline soil organic matter varied with soil depth with the highest percentage observed on the 0-15 cm (9.4%) followed by 15-30 cm (6.2%) and 30-45 cm (5.2%). Using the assumption that 58% of organic matter is organic carbon and soil bulk density is 1.07 g/cm^3 for Red River Clay soils (MAFRI, 2008), soil organic carbon stock is calculated and presented in Table 174. An increase in SOC is observed at all soil depths, which is consistent with soil N, P and K.

Table 174. Evolution of SOC stocks in the 6-year study

Location	Climate zone	Soil type	Depth (cm)	Duration (Years)	Baseline C stock (tC/ha)	Current C stock (tC/ha)	Additional stock (tC/ha/yr)
Prairie Region (MB)	Cool temperate Moist	Solonetzic Black Chernozem	0-15	6	87.23	144.29	+9.51
			15-30		57.72	89.37	+5.28
			30-45		48.41	73.26	+4.14

6. Other benefits of the practice

6.1. Improvement of soil properties

Changes in soil properties at a depth of 0-15 cm are presented below. In general, an increase in soil macronutrients (N, P, and K) is observed. Salts concentrations decreased over time.

Table 175. Changes in soil properties

Soil Properties	2013	2019
NO_3-N (ppm)	1.83 (0.29)	7.67 (5.03)
NH_4-N (ppm)	5.63 (0.80)	12.13 (3.82)
P-Olsen (ppm)	31.33 (9.29)	38.33 (20.21)
K (ppm)	280.33 (41.77)	476.67 (35.73)
Ca (ppm)	4452.33 (363.53)	4751.33 (471.57)
Mg (ppm)	1577.33 (247.69)	1713.67 (364.66)
Na (ppm)	94.66 (22.50)	66.66 (4.04)
Cl (ppm)	15.5 (2.78)	11.67 (7.37)
Salts (mmhos/cm)	0.84 (0.36)	0.52 (0.04)
pH	6.43 (0.06)	6.63 (0.25)
CEC (meq)	36.53 (3.15)	39.53 (5.34)

6.2 Minimization of threats to soil functions

Table 176. Soil threats

Soil threats	
Nutrient imbalance and cycles	Sequestration of excess N, P, and K
Soil salinization and alkalinization	Reduction of salinization by managing the water table through willow buffer water usage/evapotranspiration
Soil contamination /pollution	Mitigation of agricultural fertilizer runoff

6.3 Mitigation of and adaptation to climate change

Using CBM-CFS3 simulations, the average potential annual rate of carbon sequestration in cumulative harvest was estimated at 5.4 tC/ha/yr for marginal lands on the Canadian prairies (Amichev *et al.*, 2012).

7. Potential drawbacks to the practice

7.1 Decreases in production (Food/fuel/feed/timber/fibre

Although data is not available for the Prairie region, reduced agricultural output due to land-use tradeoffs was recorded from Eastern Canada (Lantz, Chang and Pharo, 2014). The maintenance of buffer strips is a crucial factor governing their longer-term nutrient retention effectiveness. Without maintenance, buffer strips are known to become a potential source of nutrients rather than a sink (Hille *et al.*, 2019).

8. Recommendations before implementing the practice

Before a willow riparian buffer is implemented, it is necessary to investigate regional regulations and guidelines that may impact the ability to incorporate the buffer (Hénault-Ethier *et al.*, 2019). It is also essential to work with regional experts to receive recommendations on selecting suitable hardy cultivars (Nissim *et al.*, 2013) as well as appropriate planting, maintenance, and management procedures (Truax *et al.*, 2017; Fortier *et al.*, 2010). Proper planning and site preparation will lead to greater success of the planting and investigating the end-use of the biomass, necessary harvesting regime/equipment, and finding local markets before implementing the willow riparian buffer practice.

9. Potential barriers for adoption

Table 177. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Suitable willow cultivars that match the site's environmental conditions must be selected to maximize the buffer's effectiveness (Nissim *et al.*, 2013). Limitations may arise from the regional availability of desired cultivars.
Economic	Yes	Adoption of willow riparian buffers may be limited by costs associated with the loss of land previously used for crop production, initial establishment, and maintenance (Lantz, Chang and Pharo, 2014; Ssegane *et al.*, 2016).
Institutional	Yes	Local legislation in some jurisdictions may limit the management (harvesting) of riparian buffer strips within legislated buffer zones limiting the removal of above biomass and impact of nutrient removal.
Knowledge	Yes	Knowledge of agroforestry systems by grain and livestock producers, who operate the land, is limited. The use of appropriate management and maintenance practices, including the selection of suitable cultivars, use of black plastic mulching, and regular harvesting, will influence the long-term success of the buffer (Truax *et al.*, 2017; Fortier *et al.*, 2010).
Other	Yes	Although the production of biomass can provide financial incentives for land managers, harvesting of small areas may be challenging due to machinery access difficulties (Zak *et al.*, 2019).

Photos

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Photo 90. Paired row willow growth at the end of the 2013 establishment year growing season, August 27, 2013

Photo 91. Vegetation growth after three years of establishment, July 26, 2016

Photo 92. Whitetail deer spotted along Elie Willow Buffer, October 8, 2016

Photo 93. Rhonda Thiessen using Felco shears to harvest willow buffer biomass subplot, November 7th, 2016

Photo 94. AAFC employees harvesting Elie willow buffer biomass - November 18th, 2019

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43. Response of soil carbon to various combinations of management practices (annual-perennial rotation system, animal manure application, reduced tillage) in Quebec, Canada

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1. Related practices

Crop rotations, manure applications, reduced tillage.

2. Description of the case study

In Eastern Canada, most dairy farms present some form of integrated livestock and crop production. They are generally based on hay or silage production, but small cereals, maize (silage and grain), and soybeans are also produced for on-farm use or as an opportunity source of revenue. Also, as cattle are generally kept in the barn for most of the year, animal manure is accumulated in storage facilities (either in liquid or solid form) and disposed of on the farm land during the growing season and the post-harvest period before onset of winter (soil freezing). The integration of crops and livestock productions results in combining several management practices which will influence soil carbon (C) stocks. Among them, annual-perennial rotation systems usually lead to higher soil organic C stocks than annual systems (Gregorich, Drury and Baldock, 2001). Also, animal manure application generally leads to soil C increase in comparison to mineral fertilization, but studies focusing on the soil C stocks to liquid animal manure are scarce compared to the literature on solid manure (Maillard and Angers, 2014). In addition, the response of C stock to liquid manure seems to be quite variable (Maillard *et al.,* 2016). Finally, adoption of reduced tillage generally results in higher soil C stocks in surface soil layers in comparison to conventional till (Angers and Eriksen-Hamel, 2008). All these practices can interact together but relatively few long-term field studies have investigated their combined effects. In this context, soil C stocks were measured

21 years after the implementation of an experiment including a cereal-perennial forage rotation compared to a cereal monoculture in combination with two nutrient sources (liquid dairy manure application vs. mineral fertilization) and two fall primary tillage practices (moldboard vs. chisel plowing).

3. Context of the case study

The case study is located at the Normandin Research Farm of Agriculture and Agri-Food Canada (48°50'42''N, 72°32'25''W) in the province of Quebec, Canada and was initiated in the fall of 1989. The area is characterized by a cool temperate and moist climate (IPCC, 2006) with mean annual temperature of 1.1°C, and mean annual precipitation of 849 mm. The silty clay soil belongs to the Labarre Series and is classified as a Humic Gleysol (Lamontagne and Nolin, 1997; SCWG,1998). The 0-15 cm soil layer had the following characteristics at the initiation of the study: pH of 5.6, bulk density of 1.36 g/cm^3, 26.1 g/kg organic C, 49 percent clay and 8 percent sand. Prior to the implementation of the study, the site was under a barley (*Hordeum vulgare*)-alfafa (*Medicago sativa*) rotation. More details on the site, soil and experimental design of this study are presented in Bissonnette *et al.* (2001) and Maillard *et al.* (2016). The compared crop rotations were a continuous spring barley monoculture (MON) and a 3-yr cereal-perennial forage rotation (ROT) (Photo 95). From 1989 to 1999, the cereal-perennial forage rotation consisted of barley underseeded with a forage mixture of timothy (*Phleum pratense*) and red clover (*Trifolium spp.*) . Since 2000, orchard grass has replaced timothy in the forage mixture. Barley was harvested at the end of the 1st year of rotation, followed by two years of forage production. The two fall primary tillage practices consisted of chisel plow (CP) to a depth of 15 cm, and moldboard plow (MP) to a depth of 20 cm. The two crop rotations involved different tillage frequencies: yearly in the cereal monoculture, and at the end of the forage phase in the cereal-forage rotation (i.e. once every three years). The two nutrient sources were a complete mineral fertilizer (MIN) and liquid dairy manure (LDM) (Photo 96). The experiment was arranged as a split-split-plot design with crop rotation as the main plot, tillage system as the subplot, and nutrient source as the sub-subplot. Soil samples for C measurement in the surface soil layer (0-20 cm) and in the whole-soil profile (0-50 cm) were taken in 2010, 21 years after the initiation of the experiment.

4. Possibility of scaling up

About 80 percent of Canada's dairy farms are located in the provinces of Quebec and Ontario (Dairy farmers of Canada, 2016), and dairy production is the most important agricultural sector in these two provinces. These dairy farms can be defined as "integrated crop-livestock operations" and typically include the management practices described in this case study. However, in the last years, the surface area under perennial forages in Eastern Canada has decreased and has partly been replaced by annual crops, including silage maize, leading to a decline in soil C stocks (McConkey *et al.*, 2017). For example, in the province of Quebec, the surface area under hay decreased from 842 000 ha to 658 500 ha between 2007 and 2016, whereas the area under silage maize increased from 47 000 to 66 400 ha (MAPAQ, 2018). The case study described above clearly demonstrates the benefits of recycling dairy manure on soil health and fertility, especially when combined with perennial forage-based rotations. These beneficial management practices should be maintained and encouraged to maintain or increase soil C. This specific case-study could be applied to any regions exposed to a cold, humid climate. Other studies might be necessary to validate the results under warmer and drier conditions.

5. Impact on soil organic carbon stocks

It is first noteworthy that the effects of the different practices varied according to the soil depth considered. Indeed, as we see in Table 178, among the beneficial management practices, the cereal-perennial forage rotation was the practice showing the greatest impact on soil C stocks both in the surface soil layer (0-20 cm) and the soil profile (0-50 cm). Both liquid dairy manure application (compared to mineral fertilizer) and chisel plowing (compared to moldboard plowing) significantly increased soil C stocks in comparison to their respective reference practices (mineral fertilization and moldboard plow) when considering the 0-20 cm soil layer. However, the effects of those practices were not significant when the 0-50 cm soil profile was considered. Combining the three beneficial management practices together (ROT-CP-LDM) resulted in the greatest soil C storage potential both in the surface layer and the soil profile.

Table 178. Soil Organic Carbon stocks changes observed in the study site over a 21-year period

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Depth (cm)	More information	Reference
80.2	0.74 (ROT)	0-50	The baseline stock corresponds to the cereal monoculture (MON). The increase is statistically significant.	Maillard *et al.* (2016)
85.3	0.26 (LDM)		The baseline stock corresponds to mineral fertilization (MIN). The increase is not statistically significant.	
71.0	-0.06 (CP)		The baseline stock corresponds to moldboard plow (MP). The change is not statistically significant.	
85.8	0.81 (ROT-CP-LDM)		The baseline stock corresponds to the cereal monoculture combined with moldboard plow and mineral fertilization (MON-MP-MIN). The change is statistically significant.	Maillard *et al.* (2016); Unpublished
50.8	0.63 (ROT)	0-20	The baseline stock corresponds to MON. The increase is statistically significant.	Maillard *et al.* (2016)
53.9	0.33 (LDM)		The baseline stock corresponds to MIN. The increase is statistically significant.	
54.2	0.30 (CP)		The baseline stock corresponds to MP. The increase is statistically significant.	

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Depth (cm)	More information	Reference
48.7	1.23 (ROT-CP-LDM)		The baseline stock corresponds to MON-MP-MIN. The change is statistically significant.	Maillard *et al.* (2016); Unpublished

Climate is cool temperate moist, soil type is Humic Gleysol

6. Other benefits of the practice

6.1. Improvement of soil properties

With the increase of soil C observed in the 0-20 cm soil layer under the beneficial management practices (perennials, chisel plowing, manure application), it is expected to observe other benefits on soil quality in general. Indeed, as the main component of organic matter, soil C provides a range of other benefits, (e.g. improvement of soil aggregation, water infiltration, source of nutrients for crops). This was confirmed by the work of Bissonnette *et al.* (2001) who measured selected surface (0-7.5 cm) soil properties during the first seven years of this case study (Bissonnette *et al.*, 2001). Overall, liquid dairy manure application increased water-stable aggregation over mineral fertilization. On average, tillage methods had little effect on aggregation in the monoculture, whereas chisel plow resulted in better soil aggregation than moldboard plow in the rotation. Overall, the microbial biomass C content and the alkaline phosphatase activity were positively affected by liquid dairy manure application both in the cereal monoculture and in the rotation. In addition, similarly to soil C, soil N stocks were higher under the beneficial management practices (D'Amours, 2018).

Soil P was also studied in the experiment. After 10 years, the perennial-based rotation resulted in greater labile Pi and Po pools than the monoculture in the 30- to 60-cm layer. When applied in the rotation system, LDM resulted in the largest total labile P pool, whereas the LDM resulted in about 20 percent higher degree of soil P saturation as expressed by the Pox/(Feox +Alox) molar ratio than the MIN in the 0- to 30-cm layer. Our observations stressed that the impacts of crop sequences and nutrient sources on soil labile P extended deeper into the profile than the disturbance caused by primary tillage (Zheng, MacLeod and Lafond, 2004).

6.2 Minimization of threats to soil functions

Table 179. Soil threats

Soil threats	
Soil erosion	Increase of soil C stock and improvement of aggregation can prevent soil erosion and soil losses.
Nutrient imbalance and cycles	The soil C content is linked to soil fertility. The soil N and P contents were generally improved under the beneficial management practices.

6.3 Increases in production (e.g. food/fuel/feed/timber)

The effects of the beneficial management practices on forage and barley grain production were assessed during the first 21 years of the experiment (Lafond *et al.,* 2017). Barley grain yields were 14 percent higher with the moldboard than with chisel plowing during the first 10 year of the experiment only. In the perennial-based rotation, grain yields were comparable between the two fertilizer sources, but in the cereal monoculture, liquid dairy manure resulted in lower yields compared with mineral fertilization. In contrast, forage yields were 11 percent higher under liquid dairy manure application than under mineral fertilization. In the long term, perennial forages and barley can be sustainably produced in rotation without productivity loss using liquid dairy manure and either moldboard plow or chisel plow. Residual N effects and non-N benefits from manure and rotation are identified as important factors contributing to cereal and forage productivity.

6.4 Mitigation of and adaptation to climate change

N_2O emissions from soils were measured for two consecutive years in this case study in 2011 and 2012, but only on all phases of the cereal perennial-forage rotation receiving mineral fertilization or dairy cattle manure in combination with moldboard plowing (Chantigny, 2013). The objective was to establish emission factors for the entire rotation under moldboard plowing with animal manure in comparison to mineral fertilization. The average amount of N_2O-N emitted for the entire rotation was:

- For mineral fertilization: 0.718 kg N/ha for barley + 1.223 for first year of forage + 2.455 for second year of forage = 4.396 kg N/ha;
- For manure fertilization: 2.304 kg N/ha for barley + 0.709 for first year of forage + 0.846 for second year of forage = 3.859 kg N/ha;

N_2O emissions for the second year of forage were related to the moldboard plowing of the forage stand in the fall. Despite N_2O emissions tending to be larger with LDM than MIN in the barley phase of the rotation, the opposite trend was found during the forage phase of rotation. From these emission values, we can hypothesize that the values for three years of cereal monoculture would be 2.154 kg N/ha for MIN and 6.912 kg N/ha for LDM. Consequently, the emissions would be higher with LDM than with MIN for the cereal monoculture, whereas they are lower with LDM than with MIN for the rotation under moldboard plowing.

7. Possible increases in greenhouse gas emissions

The variability in N_2O emissions, which varied with crop rotation and nitrogen source under moldboard plowing (see 6.4), illustrate the importance of their measurement when calculating the net GHG balance of dairy farm soils, as N_2O-N emission may counterbalance the gain in SOC accumulation.

8. Recommendations before implementing the practice

The impacts of implementing these practices may vary according to climate and soil. However, we believe based on this and other studies (Angers, 1992; Poirier *et al.*, 2009; Samson *et al.*, 2020), that similar trends would apply to heavy-textured soils in similar climatic conditions.

9. Potential barriers for adoption

In general, in dairy farms of this area, crops and livestock productions are generally already well integrated. Crops are generally used on farm as feed and manures are valorized on farm.

Photos

Photo 95. Barley and forage experimental plots located at the Normandin Research Farm of Agriculture and Agri-Food Canada

Photo 96. Liquid dairy manure application on forage plots located at the Normandin Research Farm of Agriculture and Agri-Food Canada

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44. Zone Tillage of a Clay Loam in Southwestern Ontario, Canada

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1. Related practices

Zone tillage, No-till

2. Description of the case study

No-till (NT) management can reduce corn (*Zea mays L.*) yields relative to moldboard plow tillage (MP) on fine textured soils in cool humid climates. Zone tillage (ZT) consists of tilling the corn row only and leaving the interrow area uncultivated. Zone tillage increased corn yields relative to NT. In this study, SOC content, bulk density, and penetration resistance were compared both in zone and between zones for the ZT, MP, and NT tillage treatments for a Brookston clay loam soil (Typic Argiaquoll) in southern Ontario, Canada.

This case study was initiated in 1993. The initial treatments included three NT and two MP treatments, which were arranged in a randomized complete block design with four replicates. In 1996, one of the NT treatments was left as NT, while the other two NT treatments were converted into ZT. No soil disturbance occurred in the NT treatment except for planting with a no-till planter. The MP treatment included moldboard plowing to the 15- to 17-cm depth each fall and then secondary cultivation or disking and harrowing in the following spring just before planting. The ZT treatment (ZT) involved a fall tillage operation using a chisel shank and two fluted coulters which were used to cultivate the soil in 21 cm wide zones that were ~15 cm deep (McLaughlin *et al.*, 2008). The corn was planted into the middle of each zone in the following spring. Corn row spacing for all tillage treatments was 76.2 cm, hence MP had 100 percent of the soil surface cultivated, ZT had ~28 percent of the soil surface cultivated and the soil surface was not cultivated at all with NT. During the course of the 3 year rotation, there was one fall tillage operation for ZT (before the corn phase) while the soybean and winter wheat phases of the ZT treatment were under no-till. In contrast, fall tillage was used every year for the 3 crops under MP.

3. Context of the case study

Research was conducted on a Brookston clay loam soil located at the Eugene F. Whelan Research Farm, Agriculture and Agri-Food Canada, Woodslee, ON (42°13′ N, 82°44′ W). The average soil texture in the top 15 cm is 28 percent sand, 35 percent silt, and 37 percent clay by weight, and the soil pH ranges from 6.1 to 6.5. The mean annual air temperature and precipitation at the field site are 8.7°C and 827 mm, respectively. Soil erosion and surface runoff are negligible because surface slopes are <1 percent.

4. Possibility of scaling up

Zone tillage could be applied in multiple geographic areas and climatic condition, primary focus for use in areas with fine textured soils and cool, humid climates. The benefits of NT are not consistent across soil type, climate, and landscape. For instance, continuous NT on the cool, humid, fine-textured soils of southwestern Ontario generally reduces corn yields because of excess crop residues, surplus soil water, and lower soil temperatures in the spring, which in turn reduces corn emergence and impairs early corn growth (Drury *et al.*, 1999, 2003; Dwyer *et al.*, 2000; Yang *et al.*, 2008). In addition, continuous NT on fine-textured soils usually leads to increased soil bulk density and soil strength (Drury *et al.*, 2003; López-Fando and Almendros 1995; López-Fando, Dorado and Pardo, 2007), enhanced water and nutrient movement below the root zone (Franzluebbers, Causarano and Norfleet, 2009), decreased air-filled soil porosity and saturated hydraulic conductivity (Pierce, Fortin and Staton, 1992), and increased risk of seedling desiccation due to reopening of the seed planting slot (Drury *et al.*, 1999, 2003).

5. Impact on soil organic carbon stocks

Table 180 shows the additional C storage potential of NT and ZT as compared to the baseline conventional MP treatment on 0-30 layer depth, in the study plot (Canada, Cool temperate moist climate). Soils are Brookston clay loam soil (Typic Argiaquoll in USDA Soil Taxonomy).

Assumptions:

1) CT was in equilibrium so that the quantity of SOC in 2009 was similar to that in the fall of 1993 and the fall of 1996.
2) The impacts of ZT over NT were from the fall of 1996 to the fall of 2009 (13 years)
3) The C sequestration rate for NT was from the fall of 1993 to the fall of 2009 (16 years).
4) The rate of change in SOC sequestration is assumed to be linear over time.
5) The initial SOC for the ZT treatment in the fall of 1996 was assumed to be proportional to the change over the 16 years.

Table 180. Evolution of SOC stocks according to different tillage treatments on the study site at 0-30 cm depth

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (years)	More information	References
71.7	0	16	Conventional (Moldboard Plow) Treatment	Shi *et al.* (2006); Drury *et al.* (2012, 2006)
	62	13	No-Tillage Treatment	
	673	13	Zone Tillage Treatment	

6. Other benefits of the practice

6.1. Improvement of soil properties

ZT had the lowest bulk density and penetration resistance of the 3 tillage treatments (Shi *et al.*, 2011).

6.2 Minimization of threats to soil functions

Table 181. Soil threats

Soil threats	
Soil erosion	Reduced soil disturbance compared to Moldboard Plow treatment
Nutrient imbalance and cycles	Nutrient mixing occurs MP and in the zone with ZT but nutrient stratification would be expected under NT.
Soil biodiversity loss	Tillage has detrimental impact on earthworm populations when short and long-term NT and ZT were compared in an adjacent tillage study.
Soil compaction	Continuous NT on fine-textured soils usually leads to increased soil bulk density and soil strength, enhanced water and nutrient movement below the root zone, decreased air-filled soil porosity and saturated hydraulic conductivity, and increased risk of seedling desiccation due to reopening of the seed planting slot.

6.3 Mitigation of and adaptation to climate change

Fuel and energy saving benefits: Fuel consumption and related GHG emissions on a per hectare basis was highest for the moldboard plow at 21.6 L/ha, over three times the 6.5 L/ha for the shallow zone till (McLaughlin *et al.*, 2008).

7. Possible increases in greenhouse gas emissions

In two 3-year studies, ZT had significantly lower N_2O emissions than both NT and MP when the N fertilizer was injected at about 10 cm depth (Drury *et al.*, 2006, 2012). In particular, the N_2O emissions under ZT were 38-44 percent lower than MP whereas NT had 17-23 percent lower N_2O emissions than CT (Drury *et al.*, 2006, 2012).

8. Potential barriers for adoption

Table 182. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Climatic: ZT benefits best realized in areas with fine textured soils and cool, humid climates, in drier condition, NT benefits seen in drier conditions (Angers *et al.*, 1997)/

Photo

Photo 97. Zone tillage in the fall (September/October) following a July winter wheat harvest in preparation of spring planting of grain corn into the tilled zones in the following May

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45. Long-term no-tillage maize in Kentucky, the United States of America

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1. Related practices

No-tillage, cover cropping

2. Description of the case study

This study firstly analyzed the soil organic carbon (SOC) storage change to the 30 cm layer in a maize system during 1970-2018. Maize (*Zea mays* L.) was grown each year, followed by winter cereal cover crop. The experiment design was a split block with four replications. Each block was split vertically for tillage treatments (no-tillage and moldboard plow, Photo 98), which were assigned randomly to the two halves of each block. The nitrogen rate was 168 kg N/ha for both tillage treatments. This rate is the average nitrogen rate for maize in Kentucky during the past four decades (i.e. considered to be nitrogen-sufficient for maximizing crop yield at this site).

The tilled plots were plowed and disked with an average tilling depth of 20 cm in mid-April, about 1-2 weeks before maize planting in early to mid-May. Cereal rye (*Secale cereale* L.) as winter cover crop was sown between mid-September and mid-October without tillage. The dead biomass of cover crop was left on the soil surface before spring tillage. The nitrogen source, ammonium nitrate, was broadcasted about one week after planting. Shredded maize residues were left on the soil surface following maize harvest.

Secondly, based on observations on crop production and soil carbon, we calibrated and evaluated the performance of an agroecosystem model (DLEM-Ag) in simulating SOC. After that, we predicted SOC changes as affected by no-tillage and cover crop under future climate scenarios (i.e., the representative carbon pathway (RCP) 2.6 and 8.5) in 2019-2099. The RCP 2.6 represents a low emission scenario with significant climate action, aiming to limit the increase in global mean temperature to less than 2 °C by 2100. The RCP 8.5 represents the business-as-usual high emission scenario, yielding a range of temperature outcomes of +4.0 to 6.1 °C by 2100 (IPCC, 2014).

3. Context of the case study

The long-term tillage experiment was conducted at the University of Kentucky Spindletop Farm, near Lexington, Kentucky, the United States of America (N 38°07′24″, W 84°29′50″). The soil at the study site is a moderately weathered, well-drained Maury silt loam (fine, mixed, semiactive, mesic Typic Paleudalf) on a 1 to 3 percent slope without evident rill erosion. The native vegetation in the area was mostly hardwood forest. The Maury soil, however, has a thicker and darker colored surface horizon than is normal for soils formed under forest vegetation, indicating influence from grass vegetation. Before establishing the experiment in 1970, the site had been a bluegrass (*Poa pratensis* L.) pasture for about 50 years (Frye and Blevins, 1996). The experimental site is characterized by a rainfed moderate humid climate with a mean annual temperature of 13.1°C and a mean annual precipitation of 1 222 mm (1970-2018).

4. Possibility of scaling up

This study was conducted in a warm-wet region with well-drained soils. It is reported that crop responses to NT often performs better in dry climates or well-drained soils in humid climates (Triplett and Dick, 2008). What applies to this study site should be cautiously interpreted, as the effectiveness in promoting productivity and carbon sequestration through NT and cover crops is spatiotemporally heterogeneous.

5. Impact on soil organic carbon stocks

Initial soil carbon contents to 30 cm before the experiment establishment was 52.23 tC/ha in the bluegrass sod plots adjacent to the experiment plots (Blevins, Thomas and Cornelius, 1977). In 2018 fall, soil carbon contents to 30 cm are 51.66 tC ha^{-1} and 41.19 tC/ha in the NT-CC (no-tillage with cover crop) and MP-CC (moldboard plow with cover crop) plots, respectively. As to the simulated SOC, it was 53.43 tC/ha under NT-CC and 42.52 tC/ha under MP-CC in 2018 (Huang *et al.*, 2020). Soil carbon sequestration is 0.22 tC/ha/yr with NT-CC compared with the business-as-usual practice (MP-CC). The model predicted that NT-CC and MP-CC would sequester soil carbon by 0.09 ± 0.02 tC/ha/yr and 0.06 ± 0.02 tC/ha/yr, respectively, under the RCP 8.5 scenarios, largely due to the enhanced biomass production of cover crop. Moreover, NT-CC would reduce carbon loss compared to MP-CC in the RCP 2.6 scenarios. The negative effect on SOC storage in the RCP2.6 scenarios is due to the relatively stabled crop production and slightly increased soil CO_2 emissions (Table 183).

Table 183. Long-term evolution of SOC stocks at 0-30 cm depth, in Lexington, Kentucky, the United States of America

Baseline C stock (tC/ha)	Additional C storage potential (tC/ha/yr)	Duration	More information	Data type
41.19[ǂ]	0.22	1970-2018	NT-CC VS.MP-CC	Obs.
52.23[*]	-0.01	1970-2018	NT-CC	
52.23[*]	-0.23	1970-2018	MP-CC	
53.43[*]	0.09 ± 0.02[**]	2018-2099	NT-CC (RCP 8.5)	Mod.
42.52[*]	0.06 ± 0.02[**]	2018-2099	MP-CC (RCP 8.5)	
53.43[*]	-0.00 ± 0.02[**]	2018-2099	NT-CC (RCP 2.6)	
42.52[*]	-0.02 ± 0.01[**]	2018-2099	MP-CC (RCP 2.6)	

Source: Data available in Huang et al. (2020)

Climate is Warm Temperate Moist and soils are classified as Maury silt loam

Obs. represents values derived from field observations. Mod. (RCP 2.6 and RCP 8.5) represents model simulations under the representative carbon pathway 2.6 and 8.5 scenarios, respectively, for the future period

[ǂ] Baseline value of C stock is the stock value under a business as usual practice

[*] Baseline value of C stock is the stock value at t=0

[**] Mean and standard deviation of results derived from different climate model databases

6. Other benefits of the practice

6.1. Improvement of soil properties

No-tillage enhances soil aggregation and structural stability compared to conventional tillage practices at this site (Perfect and Blevins, 1997). Another advantage of NT is maintaining soil moisture due to reduced evaporation and increased infiltration in the presence of surface cover and macropores (Blevins *et al.*, 1983). No-tillage also increases activities of beneficial organisms such as earthworms by not disrupting their life cycles. A recent study shows that NT increases microbial community diversity because of the greater heterogeneity, different moisture conditions, and higher organic matter in NT compared with tilled soils (Liu *et al.*, 2020). Soil compaction is often a problem with heavy machinery equipment; however, bulk density differences among tillage treatments are not significant (Ismail, Blevins and Frye, 1994).

6.2 Minimization of threats to soil functions

Table 184. Soil threats

Soil threats	
Soil erosion	With minimal soil disturbance and residue mulch, NT reduces soil loss.
Nutrient imbalance and cycles	Nutrients released from the decomposition of crop residues and cover crop biomass foster nutrient cycles.
Soil compaction	Soil compaction is not obviously found under long-term NT.
Soil water management	NT reduces evaporation and enhances soil water retention due to surface residue cover (Blevins *et al.*, 1983).

6.3 Increases in production (e.g. food/fuel/feed/timber)

Average maize yields with NT exceed those with MP during most years during 1970 and 2018, so do the average yields across this period (Grove *et al.*, 2009). These agree with the findings that NT yields are typically higher than conventional tillage yields on moderate- to well-drained soils (Triplett and Dick, 2008). The higher soil moisture under NT as compared to MP throughout the growing season may carry the NT crop though short drought periods without severe water stresses (Blevins *et al.*, 1983). The higher maize yields under NT than MP indicates more efficient utilization of N with NT maize production. Cover crops also had greater biomass production in the NT system than in the CT system. One possible explanation could be that the higher soil moisture content with NT, as compared to CT, also benefited winter cover crop growth. In addition, greater SOC build-up in NT could provide greater mineralizable N. This may be important for cover crop growth because cover crops are not fertilized - they just receive some residual fertilizer N and N mineralized from SOM.

6.4 Socio-economic benefits

The adoption of NT will reduce fuel costs, labor, and equipment cost (less machinery input required and lower machinery expenses through lower wear and tear). It may also improve the timeliness of field preparation. No-tillage production reduces soil loss and makes more profitable crop selection possible.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 185. Soil threats

Soil threats	
Nutrient imbalance and cycles	The mineralization rate of organic matter can be slower in NT soils. In short-term, adequate fertilizer is needed to ensure crop productivity (Blevins *et al.*, 1983). Nutrient stratification is greater under NT (Díaz-Zorita and Grove, 2002).
Soil acidification	Surface acidification can be problem associated with NT (Blevins *et al.*, 1983).

7.2 Decreases in production (Food/fuel/feed/timber/fibre

The higher soil moisture content in NT systems may delay soil warm up in spring, which will prevent seed emergence and lead to poor establishment. In addition, greater soil penetration resistance and bulk density are commonly observed in NT soils compared with tilled soils. Such changes in soil properties will affect root development and, therefore, crop productivity. Crop residues from previous years could also increase the risk of pests and diseases.

8. Recommendations before implementing the practice

It is necessary to understand the soil physical, chemical, and hydrological properties before implementing NT. It is highly recommended for well-drained soils and soils with high erosion potential. We also recommend to constantly monitor soil pH and apply lime when necessary. If NT fields must be occasionally be tilled, these fields should be returned to NT management as quickly as possible.

9. Potential barriers for adoption

Table 186. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	Long history of conventional tillage practices and small farms that have traditionally been intensively managed.
Economic	Yes	Extra input for seeds, herbicide, and fertilizer.
Knowledge	Yes	Skills to operate NT equipment.
Natural resource	Yes	Climate and soil conditions in some regions might not suitable for NT.
Other	Yes	Management of herbicide resistant weeds, SOC and nutrient stratification, and risks for compaction, runoff, and acidification are constrains to continuous NT in KY and the Midwest.

Photos

Photo 98. Moldboard plow (left) and no-tillage (right) maize with cover crop biomass mixed in soil layers and left on the soil surface, respectively, in Spindletop Farm, Lexington, KY

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46. Deficit irrigation scenarios using sprinkle irrigation system in western Kansas, the United States of America

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1. Related practices

Adequate irrigation practices, No tillage

2. Description of the case study

Deficit irrigation is a water management strategy to cope with the shortage of irrigation water; it is adopted to irrigate only during the water sensitive growth stages of a crop. The effects of deficit irrigation amounts on SOC sequestration potential and variation of selected soil physical properties were quantified at Garden City under six irrigation scenarios of 66, 86, 117, 152, 182 and 217 mm and at Tribune under three irrigation scenarios of 127, 254 and 381 mm and no tillage condition, respectively (Blanco-Canqui *et al.*, 2010). Irrigated agriculture promotes the production of near surface organic biomass and encourages its organic decomposition by increased sub soil moisture content and micro-biological activity. Irrigation could also increase the soil inorganic carbon (SIC) concentration due to high carbonate and bicarbonate concentrations in irrigation water and their subsequent precipitation after application as calcium salts, thus increasing the overall carbon sink capacity of the irrigated lands. Flood and drip irrigation systems with different amounts of applied water have shown contrasting results on the soil SOC capacity (Guo *et al.*, 2017). Therefore, this case study is reported particularly due to two reasons. First, because irrigation is globally practiced on a large area of 275 million hectare which has a very high potential of SCO sequestration and second, because this study adopts a scenario-based approach with the application of different amounts of irrigation water through sprinkler irrigation system to investigate the response of SOC sequestration to irrigation depth. The scenario-based approach makes this study highly adoptable to different irrigation regions where water availability is highly variable due to system allocations and efficiencies and the farmers tend to apply deficit irrigation to cope with the water shortages.

3. Context of the case study

The area has temperate continental climate; therefore, the study is highly adoptable at regional scale with similar climatic conditions. Deficit irrigation was applied with sprinkle irrigation system to study the effect of different irrigation depths on C concentration. The study was conducted on 6 x 4 = 24 plots at Garden City and 3 x 4 = 12 plots at Tribune in Western Kansas, the United States of America. The soil is composed of silt loam with less than 1 percent field slope. Soil core and bulk soil samples were collected from the plots for the determination of soil bulk density and C concentration. The bulk density was determined using the oven dried soil core method (Grossman and Reinsch, 2002). The bulk soil samples were air-dried and passed through a 0.25 mm sieve. The samples were tested for C concentration on mass basis (g/kg) using the dry combustion method (Nelson and Sommers, 1983) with and without pre-treatment of samples with 10 percent HCl v/v. Organic C was determined from the acid treated samples, while inorganic C was computed from the difference of C concentration of acid treated and untreated samples. The area-based C concentration (tC/ha) was then computed using the soil bulk density and the mass based C concentration. The C concentration was also determined using the equivalent mass basis to account for the differences in bulk density. However, no significant difference between the two methods was found, the result of C concentration determined on mass basis are presented below.

4. Possibility of scaling up

The study results could be valid for large areas with significant difference in summer and winter mean temperature, such as most of the North America, central Asia and west Asia.

5. Impact on soil organic carbon stocks

Table 187. Evolution of SOC stocks under irrigated crops in Garden City and Tribune, the United States of America

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	Duration (Years)	More information
11.2	1.04	5	When irrigation is increased from 66 to 217 mm, the difference in C concentration is significant in 0-10 cm depth of soil. Higher storage potential is due to increase in soil biomass.
6.75	0.22	8	When irrigation is increased from 127 to 381 mm, the difference in C concentration is significant in 5-10 cm depth of soil.

Source: Data from Blanco-Canqui et al. (2010)

Climate is warm temperate dry and soils are classified as silt loam

6. Other benefits of the practice

6.1. Improvement of soil properties

Changing the irrigation depth from the minimum to the maximum experimental values has no effect on the soil bulk density and particle size distribution at both sites. However, the amount of macro aggregates has significantly increased in the 5 cm to 10 cm depth under increasing irrigation at the Garden City and Tribune. The effect of irrigation on increased amount of macro-aggregates at the two sites is summarized in Table 188.

Table 188. Increase in the amount of macro aggregates (g/kg) with increased irrigation depth

Size of macro aggregates (mm)	Garden city		Tribune	
	Irrigation = 66 mm	Irrigation = 217 mm	Irrigation = 127 mm	Irrigation = 381 mm
1-2	29 g/kg	66 g/kg	37 g/kg	58 g/kg
4.75-8	15 g/kg	50 g/kg	18 g/kg	58 g/kg

6.2 Minimization of threats to soil functions

Table 189. Soil threats

Soil threats	
Soil erosion	An increase in the SOC concentration due to irrigation results in soil structural development and increased aggregate stability which ultimately reduce soil erosion.
Nutrient imbalance and cycles	The increase in SOC concentration with irrigation was attributed to the increase in biomass which is a rich source of nitrogen.
Soil salinization and alkalinization	Soil salinization occurs due to the accumulation of inorganic carbonate salts of calcium and magnesium. The application of different amounts of irrigation had no effect on the soil inorganic carbon (CO_3^{2+}) concentration.
Soil biodiversity loss	Increase in the formation of macroaggregates is a sign of increased soil biodiversity.
Soil water management	Increased soil moisture.

6.3 Impacts on production and socio-economic impacts

This case study does not address explicitly the impacts of irrigation on crop production or its socio-economic impacts, but overall irrigation is widely practice to increase crop productivity. Irrigation reduces the unnecessary water stress during the critical growth periods of crops and provides a mean to carry the plant nutrients necessary for its growth and production potential. Increase production of crops due to irrigation also improves the socio-economic condition of the farmers. It provides raw material to the agro-based industry which provide job opportunities to the local population.

6.4 Mitigation of and adaptation to climate change

This case study does not address the climate change mitigation and adaptation directly. However, the projected climate scenarios for future has a high probability of reduced water supplies. In such case deficit irrigation would become a new norm to cope with water shortage and maintain optimum crop yields (Fereres and Soriano, 2007) . From this point of view the study results based on several scenarios of deficit irrigation could be used to estimate the SOC potential under climate change.

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 190. Soil threats

Soil threats	
Soil salinization and alkalinization	Area specific limitations may apply as in the case of poorly drained soils.
Soil contamination / pollution	Area specific limitations may apply as in the case of contaminated water source.
Soil sealing	Soil sealing due to irrigation can occur in the presence of clayey soil.
Soil compaction	Soil compaction can occur if the irrigation amount is increased.

7.2 Increases in greenhouse gas emissions

The effect of flood and deficit irrigation on the contribution of greenhouse gases is highly variable and is poorly understood. A review of thirty-two research article on this subject (Sapkota *et al.*, 2020) reveal that fields under continuously flood irrigation have lower CO_2 and N_2O contribution as compared to deficit irrigation. While deficit irrigation has a lower emission of CH_4. To summarize, the Global Warming Potential (GWP) was analyzed for deficit and flood irrigation and the results show that overall deficit irrigation has lower GWP as compared to flood irrigation. Hence, the optimal use of irrigation water through deficit irrigation could reduce the CH_4 emission and the net GWP.

8. Recommendations before implementing the practice

Before implementing the reported practice under a different environmental condition, it is highly desirable to numerically analyze or pilot test the practice so that the intended benefits of SOC sequestration and crop productivity are optimized.

9. Potential barriers for adoption

Table 191. Potential barriers to adoption

Barrier	YES/NO	
Economic	Yes	Sprinkle irrigation has high initial cost of installation.
Institutional	Yes	Generally, there could be some institutional limitations in managing water for the sprinkle irrigation system.

Photo

Photo 99. Sprinkler irrigation for row crops

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47. Whole orchard recycling as a practice to build soil organic carbon in the San Joaquin Valley, California, the United States of America

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1. Related practices

Organic mulch

2. Description of the case study

The Mediterranean climate of California's Central Valley is optimal for almond (*Prunus dulcis*) production. Growers in the region produce approximately 80 percent of the global supply of this high value commodity (CDFA, 2019). The region is also experiencing climate change-induced stressors, including extreme heat events and increased drought frequency. In this context, it is estimated that roughly 12 000 to 16 000 hectares of almond orchards will be removed and disposed of annually in the upcoming decade. This anticipated level of orchard turnover necessitates the development of strategies to enhance the resiliency of almond production to climate change. Traditional disposal methods for tree biomass (e.g. on-site burning or transport to co-generation plants) are no longer feasible due to air quality concerns and demand for cleaner energy sources. More importantly, these methods remove stored carbon from orchards that has accumulated over decades.

Whole orchard recycling (WOR), which is the on-site grinding and incorporation of tree biomass into soil (Photo 100 and Photo 101), can be considered a climate-smart agricultural practice to sustainably dispose of tree biomass while building soil organic carbon. The practice also yields additional benefits, such as increased water use efficiency, carbon sequestration, and cycling of plant nutrients. This case study examines soil properties in a recycled almond orchard in the southern San Joaquin Valley in California, the United States of America. The previous planting was a 20-year-old peach orchard, which was used in 2008 to establish two treatments (grind and burn) in a complete randomized block design with seven replicates. In the grind treatment (WOR), woody biomass was incorporated into the top 15 cm of soil, resulting in the return of approximately 74 t/ha of woody biomass to the soil. Similarly, the burn treatment consisted of incorporating ashes into the top 15 cm of soil. In 2017, soils were collected for analyses of physical, biological, and chemical properties, including total carbon content via combustion.

3. Context of the case study

Geographical location. This research was conducted at the University of California Kearney Agricultural Research and Extension Center in Parlier, CA, the United States of America (36°35′59.4′′N, 119°30′11.7′′W). *Pedo-climatic context.* The climate is Mediterranean with average annual precipitation and temperature of 285 mm and 17°C, respectively. Soil is a Hanford fine sandy loam. *Land-use.* Arable land used for tree crop production for more than 30 years. *Coverage of the case-study*: regional.

4. Possibility of scaling up

Orchard recycling can be used in different regional and climatic settings. The practice also is not limited to almonds and can be applied to other woody perennial crops, such as apples, grapes, walnuts, pistachios, etc.

5. Impact on soil organic carbon stocks

Whole orchard recycling in comparison to a traditional method for tree disposal sequesters a significant amount of carbon in soil (+5 tC/ha). After nine years, the grind and burn treatments had soil carbon stocks of 18.7 and 13.5 tC/ha, respectively in the top 15 cm of soil. We estimate the baseline soil carbon stock was less than 10 tC/ha. WOR resulted in an estimated additional C storage potential of approximately 0.97 tC/ha/yr over baseline. WOR also increased soil organic matter to 1.52 percent compared to the burn treatment (1.07 percent). Parameter's indicative of labile C pools, such as permanganate oxidizable carbon, water extractable carbon, and microbial biomass carbon were also significantly higher following WOR in comparison to burning (Jahanzad *et al.*, 2020; Holtz *et al.*, 2018). These estimates were obtained from a study conducted in the Central Valley of California, the United States of America, which has a warm temperate dry climate and soil of a Hanford sandy loam series, which had been under tree crop production for almost 30 years (Table 192).

Table 192. Soil carbon stocks changes on 0-15 cm depth on a Hanford sandy loam in Central Valley (California, the United States of America) over 9 years

Baseline C stock (tC/ha)	Additional C storage (tC/ha/yr)	More information	Reference
13.5	0.58	C storage potential of WOR compared to traditional tree disposal.	Jahanzad *et al.* (2020); Holtz *et al.* (2018)
10	0.97	C storage potential of WOR compared to estimated baseline C stock.	

Climate is Warm Temperate Dry

6. Other benefits of the practice

6.1. Improvement of soil properties

WOR (grind treatment) improved soil physical and biological properties in comparison to the traditional method of burning for tree disposal (Jahanzad *et al.*, 2020). Soil aggregate stability measured as mean weight diameter was significantly higher under WOR, whereas bulk density and soil compaction were reduced. Water infiltration measured as hydraulic conductivity and water storage measured as volumetric water content were higher in the grind treatment compared to burn. Effects of WOR on biological properties included significantly higher microbial biomass carbon (28 percent) and higher activities of soil carbon and nitrogen cycling enzymes. Overall, WOR improved soil health compared to the burning practice as indicated by higher Soil Health Index value (6.13 vs. 4.24, respectively) (Haney, 2015).

6.2 Minimization of threats to soil functions

Table 193. Soil threats

Soil threats	
Soil erosion	WOR increases aggregate stability and soil organic matter (Anderson, Brye and Wood, 2019; Chaney and Swift, 1984).
Nutrient imbalance and cycles	WOR increases total nitrogen contents in soil and leaf tissues, suggesting decreased potential for nitrogen leaching (Jahanzad *et al.*, 2020).

Soil threats	
Soil biodiversity loss	WOR increases intra-aggregate soil organic carbon, which may support a more diverse microbial community (Rabbi *et al.*, 2016). Free-living fungivorus and bacteriovorus nematodes increase after WOR in comparison to burning (Holtz, Doll and Browne, 2016).
Soil compaction	WOR decreases soil compaction (Jahanzad *et al.* 2020).
Soil water management	WOR improves soil water retention and water use efficiency in orchard (Jahanzad *et al.* 2020).

6.3 Increases in production (e.g. food/fuel/feed/timber)

WOR improved yield in comparison to the burn treatment (Holtz *et al.*, 2018; Jahanzad *et al.*, 2020). After nine years, kernel yield in the grind treatment was more than 19 percent higher than in the burn treatment; yield differences began in 2014 between the treatments. This increase in yield in the WOR treatment was accompanied by greater tree circumference. Trees in recycled soils were also more tolerant of deficit irrigation, raising the possibility of increasing irrigation water use efficiency via this water management practice.

6.4 Mitigation of and adaptation to climate change

WOR is a promising climate-smart strategy to sequester carbon from tree biomass that had accumulated for decades and would otherwise be lost from orchards through removal (Holtz *et al.*, 2018; Jahanzad *et al.*, 2020). Additional co-benefits of increased soil water retention, water use efficiency, total nitrogen, and greater tolerance of trees to water stress indicates WOR will enable more resiliency of almond orchards to climate changed-induced stressors.

6.5 Socio-economic benefits

Almond trees grown under deficit irrigation (80 percent evapotranspiration) in WOR soils have higher yields than trees planted in the burn treatment, which may result in a cost savings (Jahanzad *et al.*, 2020).

7. Potential drawbacks to the practice

7.1 Tradeoffs with other threats to soil functions

Table 194. Soil threats

Soil threats	
Nutrient imbalance and cycles	In the initial years of WOR, soil carbon-to-nitrogen ratios may be imbalanced, leading to nitrogen immobilization and decreased availability of inorganic nitrogen for trees. To compensate, growers may need to increase nitrogen fertilization rates (Holtz *et al.*, 2018; Jahanzad *et al.*, 2020).

7.2 Increases in greenhouse gas emissions

Carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions are impacted by WOR and change significantly with time (Culumber *et al.*, unpublished data). In the first year of a recycled orchard, CO_2 and N_2O emissions are consistently higher in wood chip amended soils than unamended soils, and N_2O emissions are strongly affected by fertilization events. In the second year following WOR, the differences in CO_2 and N_2O emissions between wood chip amended and unamended soils become much smaller, suggesting the availability of readily degradable organic matter from wood chips diminishes after the first year.

7.3 Other conflicts

Whole orchard recycling has been an expensive undertaking for growers who used to burn their orchards or haul wood debris to a co-generation facility. Growers can expect to pay from 600 to 700 USD per acre to have their orchard ground up, whether they are keeping the wood chips or not. The California Department of Food and Agriculture, Natural Resources Conservation Service, and San Joaquin Valley Air Pollution Control District are offering incentives to growers to practice WOR and build soil carbon.

8. Potential barriers for adoption

Table 195. Potential barriers to adoption

Barrier	YES/NO	
Cultural	Yes	With the incorporation of large amounts of woody biomass into soil, growers may be concerned with introduction of wood-decaying soil-borne pathogens.
Economic	Yes	Orchard recycling is more expensive (+800 to 900 USD per acre) than traditional methods for tree disposal and incentives are given to growers to offset costs of implementing the practice.
Knowledge	Yes	More studies are needed on nutrient management in recycled orchards.

Photos


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Photo 100. The process of on-site grinding at an orchard in San Joaquin Valley, California, the United States of America

Photo 101. Wood chips spread on orchard floor prior to incorporation at an orchard in San Joaquin Valley, California, the United States of America

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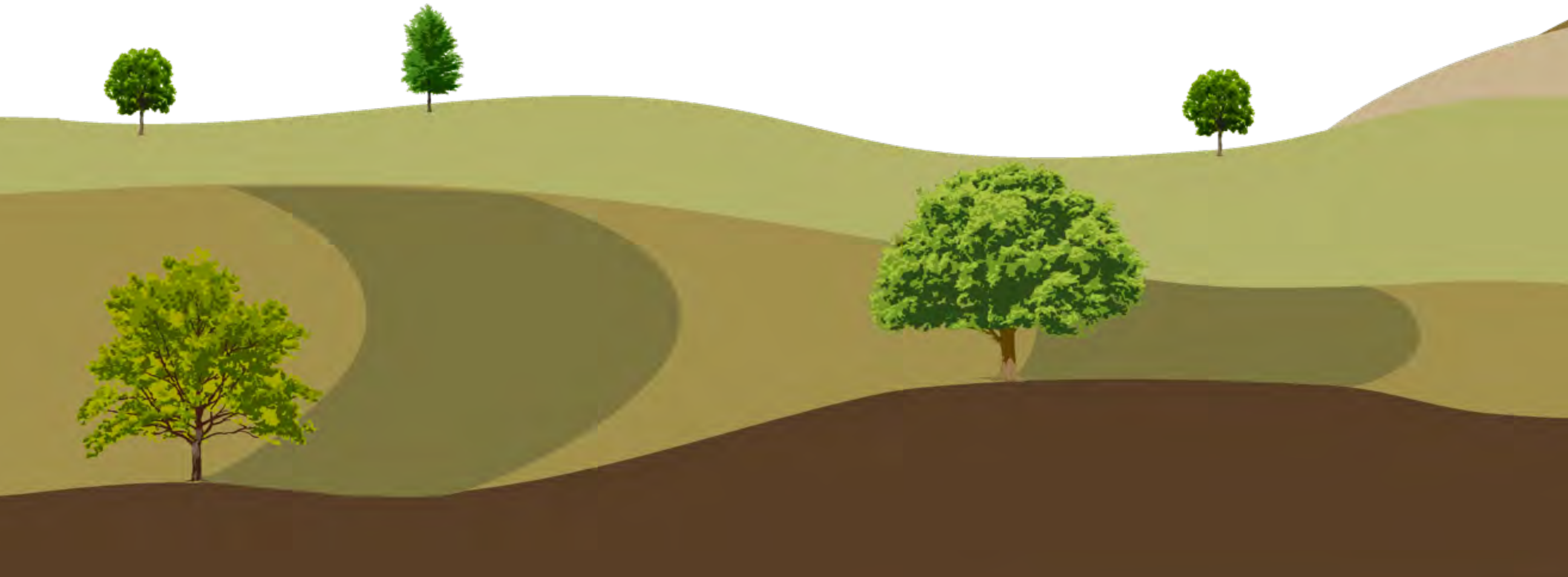

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