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Global status of black soils





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Foreword

Soils are the source of 95 percent of our food. With their rich organic matter content and high fertility, black soils are unique amongst soils. As the source of high productivity and rich ecosystem services, black soils are known as the world's food basket and have been linked with human well-being for hundreds of years. Throughout history, black soils in China have been associated with health and prosperity. In South America, the ancient heritage of black soils ensures the survival of communities and promotes the preservation of biodiversity through best traditional agricultural practices.

For centuries, these fertile soils have played a key role in the global production of cereals, tuber crops, oilseed, pastures, and forage systems. Despite representing only 5.6 percent of the global land area, these black earth belts feed not only the 223 million people settled on them, but also millions of others in countries that import commodities produced in black soils, thus significantly contributing to the global economy development and food security.

With over 828 million people facing food insecurity in 2021 and in the midst of a global fertilizer crisis, the role of soils – including black soils – is more relevant than ever. Conserving, sustainably managing and restoring our soils is vital to address global challenges such as food insecurity, poverty, the climate crisis, biodiversity loss and land degradation.

It is proven that soil organic carbon sequestration is one of the most cost-effective options for climate change adaptation and mitigation. In this regard, black soils are paramount as they contain 8.2 percent of the world's soil organic carbon stocks and can provide 10 percent of the global total soil organic carbon sequestration potential.


While 31 percent of global black soils are cultivated, great portions remain with their natural land cover of forests and grasslands. Protecting these uncultivated black soils should be a global conservation priority because of their biodiversity and the large amount of soil organic carbon they contain, all key for climate action, sustainable and resilient livelihoods and food security.

However, this rich treasure is under threat. Most black soils have already lost at least half of their soil organic carbon stocks and suffer from moderate to severe erosion, nutrient imbalances, acidification, compaction and soil biodiversity loss because of land use change (from natural grasslands to cropping systems), unsustainable use and excessive use of agrochemicals. This loss is further exacerbated by climate change.

FAO through its Global Soil Partnership is committed to the conservation and sustainable management of black soils. In this regard, it established the International Network of Black Soils, and recently published the Global Black Soils Distribution Map, which attempts to provide for the first time a global overview of the status of the world's black soils. It highlights the benefits, challenges and opportunities of black soils, with recommended actions to support a sustainable future for black soils.

I would like to convey my appreciation to the International Network of Black Soils, the world's leading black soils scientists and experts, and all FAO Members and partners who contributed to the production of this key report, raising awareness on the importance of black soils and paving a way forward to protect them.

It is our hope that all relevant stakeholders, and countries with black soils, will use the findings and recommendations of this report to protect, sustainably use and restore black soils for the food security, sustainable development and health of current and future generations.



FAO Director-General
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Abbreviations

ADEs	Amazonian dark earths	ISBS18	International Symposium on Black Soils
APP	Application	ITPS	Intergovernmental Technical Panel on Soils
BD	Bulk density	IUSS	International Union of Soil Sciences
CCFM	Compost-compound fertilizer mixture	JRC	Joint Research Centre, European Commission
CCs	Cover crops	LRR	Land Resource Region
CEC	Cation-exchange capacity	LS	Length and slope
CIESIN	Center for International Earth Science Information Network	MAFF	Ministry of Agriculture, Forestry and Fishery, Japan
CT	Conventional tillage	MARA	Ministry of Agriculture and Rural Affairs, China
DSM	Digital soil mapping	MERIT DEM	Multi-Error-Removed Improved-Terrain DEM
EC	Electrical conductivity	MODIS	Moderate resolution imaging spectroradiometer.
EPA	Environmental Protection Act	MP	Mouldboard plough
ES	Ecosystem services	NDVI	Normalized difference vegetation index
EVL	Especially valuable land	NENA	Near East and North Africa
FAO	Food and Agriculture Organization of the United Nations	NNP	Natural national park
F/B	Fungi-to-bacteria	NPP	Net primary production of vegetation
GBSmap	Global Black Soil Distribution map	NT	No tillage
GHG	Greenhouse gas	PAC	Phosphate adsorption coefficient
GHGES	Greenhouse gas emissions	POPs	Persistent organic pollutants
GPS	Global position system	RAW	Readily available water
GSOC17	Global Symposium on Soil Organic Carbon	RECSOIL	Recarbonization of Global Soils
GSOCmap	Global Soil Organic Carbon map	RUSLE	Revised universal soil loss equation
INBS	International Network of Black Soils	SAT	Crop straw amendment
INSPIRE	Infrastructure for Spatial Information in Europe	SCP	Soil conservation projects
IPCC	Intergovernmental Panel on Climate Change	SL	Sandy loam
IPHAN	National Historical and Artistic Heritage Institute	SOC	Soil organic carbon
		SOM	Soil organic matter

SPB	Soil protection board	UNEP	UN Environment Programme
SSCRI	Soil Science and Conservation Research Institute	USDA	United States of America Department of Agriculture
SSM	Sustainable soil management	USSR	Union of Soviet Socialist Republics
SUMP	Soil use and management plan	VGSSM	Voluntary Guidelines for Sustainable Soil Management
TOC	Soil total organic carbon		



Executive summary

For many generations, black soils have been prized for their rich organic matter content and the great natural fertility that results from this stored organic material. The inherent natural high fertility of black soils has led to the use of approximately one third of natural ecosystems (grasslands and forests) for crop production. Although only approximately 17 percent of global cropland occurs on black soils, in 2010, 66 percent of sunflower seeds, 51 percent of small millet, 42 percent of sugar beet, 30 percent of wheat and 26 percent of potatoes were harvested globally from black soils. The importance of crop production from black soils has been highlighted by the disruption of the global food supply caused by the current conflict in the heart of black soils.

The looming crisis of human-induced climate change has focused attention on the critical importance of the carbon locked up in the organic matter of black soils. Black soils occupy 725 million hectares of the land surface and constitute 5.6 percent of global soils but contain 8.2 percent of the world's soil organic carbon (SOC) stocks: approximately 56 billion tonnes of carbon (Pg of C). Recently, the ability of soils to remove carbon from the atmosphere and lock it up in soil organic matter (called carbon sequestration) has been proposed as an important solution to mitigate human-induced climate change. The Global Soil Organic Carbon Sequestration Potential (GSOCseq) map showed that black soils can provide 10 percent of the total SOC sequestration potential of global soils.

The need to consistently identify and promote black soils led to the establishment of the International Network of Black Soils (INBS) by FAO's Global Soil Partnership in 2017. Work by the INBS has led to a consistent definition of black soils and the first ever Global Black Soil Distribution map (GBSmap). This work was critical to identify the regions where black soils are found and to assess both the threats to these soils and the successful management approaches to counter these threats.

Major areas of black soils are found in Eurasia (Russian Federation (327 million ha), Kazakhstan (108 million ha), and Ukraine (34 million ha)), Asia (China (50 million ha), Mongolia (39 million ha)), North America (United States of America (31 million ha), Canada (13 million ha)), and Latin America (Argentina (40 million ha), Colombia (25 million ha), Mexico (12 million ha)). In many of these regions the black soils are associated with the great midlatitude grasslands: the Pampas of Argentina, the Great plains of North America, the

northeast black soil region of China, and the Forest-Steppe and Steppe regions, of the Ukraine and the Russian Federation. In all of these regions undisturbed black soils were the home for a complex assemblage of burrowing soil fauna and their actions mixed the organic matter from the grasses into upper part of the mineral soil, creating a thick, black, topsoil layer. Throughout these regions the grasslands have been extensively converted to cropland, but approximately 37 percent of black soils remain under grass cover. The INBS's GBSmap shows that an important area of black soils also occurs in forested environments. These black soils have their greatest extent in the Russian Federation and Canada and in total, approximately 29 percent of black soils are under forest cover.

Smaller areas of black soils have formed in volcanic ash deposits in countries such as Japan, in wetlands where water retards the decomposition of added organic material and in high alpine areas where the cold temperatures also slow decomposition and allow the buildup of soil organic matter. There are also significant areas where humans have formed black soils through the addition of organic matter over decades or centuries of use. Perhaps the best known of these are the Terra Preta do Índio in the Amazon basin, which have been formed by the addition of charcoal and other organic materials by indigenous groups over centuries of use. In Europe, plaggen soils have formed primarily by continued additions of manure and straw to soils. Both Terra Preta do Índio and plaggen soils demonstrate the ability of humans to fundamentally alter soils through our management practices.

The greatest threat to black soils is the loss of organic matter through both conversion of natural landscapes to agriculture and by continuing mismanagement of cultivated black soils. Studies in many black soil regions have documented losses of 20 to 50 percent of the original soil organic matter when grassland or forested black soils are converted to agriculture. These initial losses occur when stable aggregates in the soil are broken apart by soil tillage, exposing protected soil organic matter to decomposition by microbes in the soil. The carbon dioxide that is released to the atmosphere during decomposition has been a significant contributor to the atmospheric carbon pool through time.

Continuing losses of soil organic matter on cultivated black soils occur due to the physical transport of soil particles (including organic matter) by erosion. Water erosion affects all soils, but wind erosion is a particular issue in black soils of former grasslands – the drier climates these soils are found in are naturally susceptible to high rates of wind erosion. The black soil

areas of North America were particularly devastated by wind erosion during the 1930s, dust storms caused several adverse effects such as respiratory diseases causing the death of people and animals, farmlands becoming unusable, and hunger and poverty spreading across several states of North America. Continuing losses of soil organic matter through erosion have been shown to more than offset any gains in soil organic matter through carbon sequestration and hence erosion control on these soils is essential. In addition, nutrient imbalance and physical–structural deterioration should be considered as major threats to black soils. In some regions soil salinization, pollution and soil sealing due to urban advancement also occurs.

Fortunately black soils have proven to be well suited to the adoption of reduced and no-till cultivation systems (also called conservation tillage). These systems minimize or eliminate disruption of the soil surface by tillage implements and leave a cover of crop residue on the soil surface. This cover reduces water losses to the atmosphere and protects the soil from wind and water erosion as well as any erosion associated with the tillage. Adoption of reduced and no-till systems has been especially high in Argentinian Pampas and in the Great plains of North America.

This report highlights throughout the importance of two main goals: the preservation of the natural vegetation cover on black soils under grassland, forest and wetland vegetation and the adoption of sustainable soil management approaches on cropped black soils. The preservation of natural cover protects the rich organic matter levels from decomposition and release of large amounts of CO₂ into the atmosphere; the adoption of sustainable management approaches such as reduced tillage and no-till allows soil organic matter levels to stabilize and (ideally) to increase. While adoption of improved management occurs at the individual farm level, protection of natural landscapes often requires the development of monitoring systems for the status of and changes to the condition of black soils, and governance at sub-national and national levels. Currently only China has a national law in place to protect, conserve and encourage sustainable management of black soils. With this report, the International Network of Black Soils has documented the extent and importance of black soils to agricultural production and seeks to address the global threat of rising atmospheric carbon levels and the climate warming that result from this. It is hoped that the many examples of beneficial soil management and governance it contains can serve as an inspiration for the adoption of improved management approaches throughout the black soil zones of the world.



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1. Introduction

1.1 Setting the scene

Black soils - especially the Chernozems¹ of the Russian Federation steppes - were first described by Vasily Dokuchaev who named them the “Tsar of soils” or the “fourth kingdom of nature” because of their great economic, social and environmental importance (Moon, 2020).

Black soils are unique soils characterized by a thick, dark-coloured soil horizon, and rich organic matter content. Due to their high inherent fertility, black soils are known as the food basket of the world or the “giant panda in arable land” in Asia. For decades, these fertile soils have been widely cultivated, and have played a key role in global agricultural production of cereals, tuber crops, oilseed, pastures, and forage systems. Despite representing only 5.6 percent of the global land area, these black earth belts feed not only the 223 million people settled on them, but also the countries that import various black soils’ commodities, thus contributing to global economy. It is estimated that in 2010, 66 percent of sunflower seeds, 51 percent of small millet, 42 percent of sugar beet, 30 percent of wheat and 26 percent of potatoes, were harvested globally from black soils (FAO, 2022). Globally, approximately one-third of black soils are covered by crops, one-third by grasslands, and the remaining third by forests. However, this distribution varies within each region (FAO, 2022).

Most black soils have evolved to support a grassland vegetation characterized by an enormous floristic and faunistic richness, including soil biodiversity, which provides soil health and key ecosystem services such as water retention, carbon sequestration, nutrient cycling, climate regulation, among others. The V.V. Alekhin Central-Chernozem State Biosphere Reserve, located in the Russian Federation’s Kursk region, is a good example of preserved ecosystems with 7 200 species of organisms, relict vegetation and rare plant species: pristine ecosystems that can serve as reference sites to monitor soil health (Ministry of Natural Resources and Environment of the Russian Federation, 2022).

Also, black soils can harbour biodiversity hotspots for several groups of fauna (microorganisms and macrofauna), as is the case for tropical regions from Mexico, Colombia and southern Brazil (See Figure 1.1a).

The term “black soils” refers to different soil types that contain moderate to high soil organic carbon (SOC) content derived from the decomposition of animal and plant residues that will form organic matter. Black soils are paramount for climate change mitigation and adaptation as they contain 8.2 percent of the world’s SOC stocks and can provide 10 percent of the global total SOC sequestration potential, with Europe and Eurasia having the highest potential, at over 65 percent and Latin America and the Caribbean around 10 percent (FAO, 2022) (See Figure 1.1b). It is well known that carbon sequestration provides multiple benefits to the environment and humans and is one of the most cost-effective options for climate change adaptation and mitigation, as well as for fighting food insecurity, land degradation, and desertification (IPCC, 2019).

For hundreds of years, black soils have been conceived as a synonym for human well being due to the ecosystem services they provide, especially for food security and nutrition. In northeastern China during the Qing dynasty (1644 to 1912), the Manchu rulers protected their native regions, allowing the rich topsoil layer (organic matter) to develop undisturbed. Throughout history, the inhabitants of northeast China have associated black soils with the health and prosperity of their nation (Cui *et al.*, 2017). The anthropogenic black soils or Amazonian Dark Earths (ADEs) are fertile soils (Anthrosols) characterized by high content of microscopic charcoal particles, which give them their distinctive colouration (Kern and Kämpf, 1989; Schmidt *et al.*, 2014; Kern *et al.*, 2019). The ADEs are exceptionally fertile due to their high concentrations of pyrogenic charcoal, formed in pre-Columbian times by Amazonian Indigenous Peoples, who created high fertility areas, that inhabited the region between two and eight thousand years ago. This ancient heritage ensures the survival of riparian communities and promotes the preservation of biodiversity through sustainable agricultural practices. Black soils have also inspired art for their scenic and landscape beauty (See Figure 1.1c, and Photo 1.1).

¹ Chernozems are defined as black soils or dark brown due to their richness in well-humified organic matter. The thickness of the organic layer is at least 40 cm with a high base saturation (Mg^{2+} and Ca^{2+}), a neutral pH, defined bioturbation, and stable aggregation.



Figure 1.1a Global map of the soil biodiversity potential index in black soils

Source: Orgiazzi, A., Bardgett, R. D. & Barrios, E. 2016. *Global soil biodiversity atlas*. European Commission
 This map was developed by using both Global soil biodiversity atlas and GBSmap which is developed by GSP.
 FAO. 2022a. *Global Map of Black Soils*. Rome, Italy, FAO. <https://www.fao.org/documents/card/en/c/cc0236en>

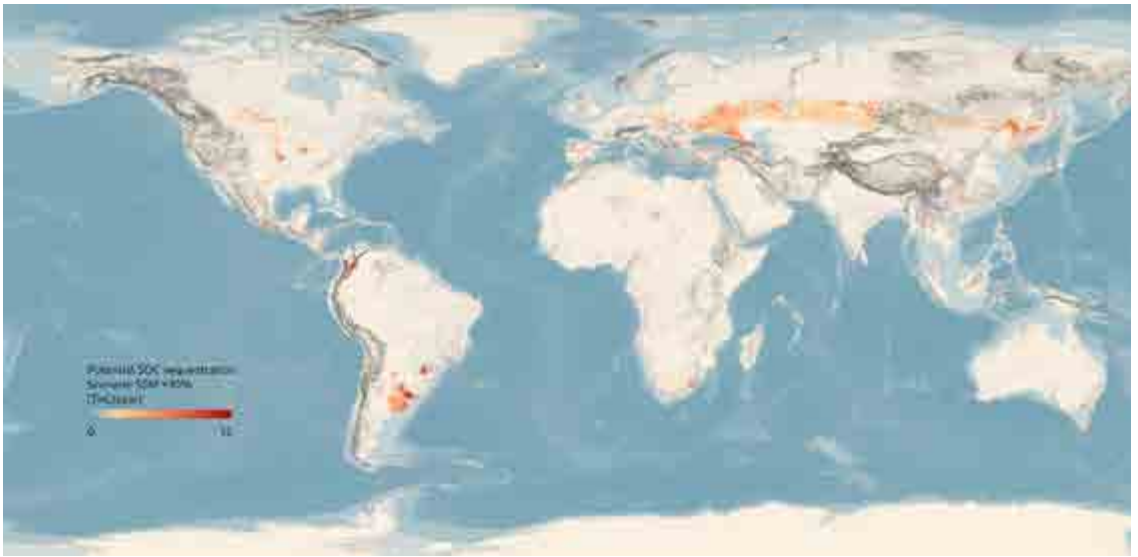


Figure 1.1b Global sequestration potential in black soil areas based on the sustainable soil management (SSM) scenario of a 10 percent increase in carbon inputs

Units expressed in tonnes of carbon per hectare, per year (annual tonnes/ha)

Source: Authors' own elaboration

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Chernic Phaeozems (Loamic. Pachic. Tonguic)
From Heilongjiang Province, China

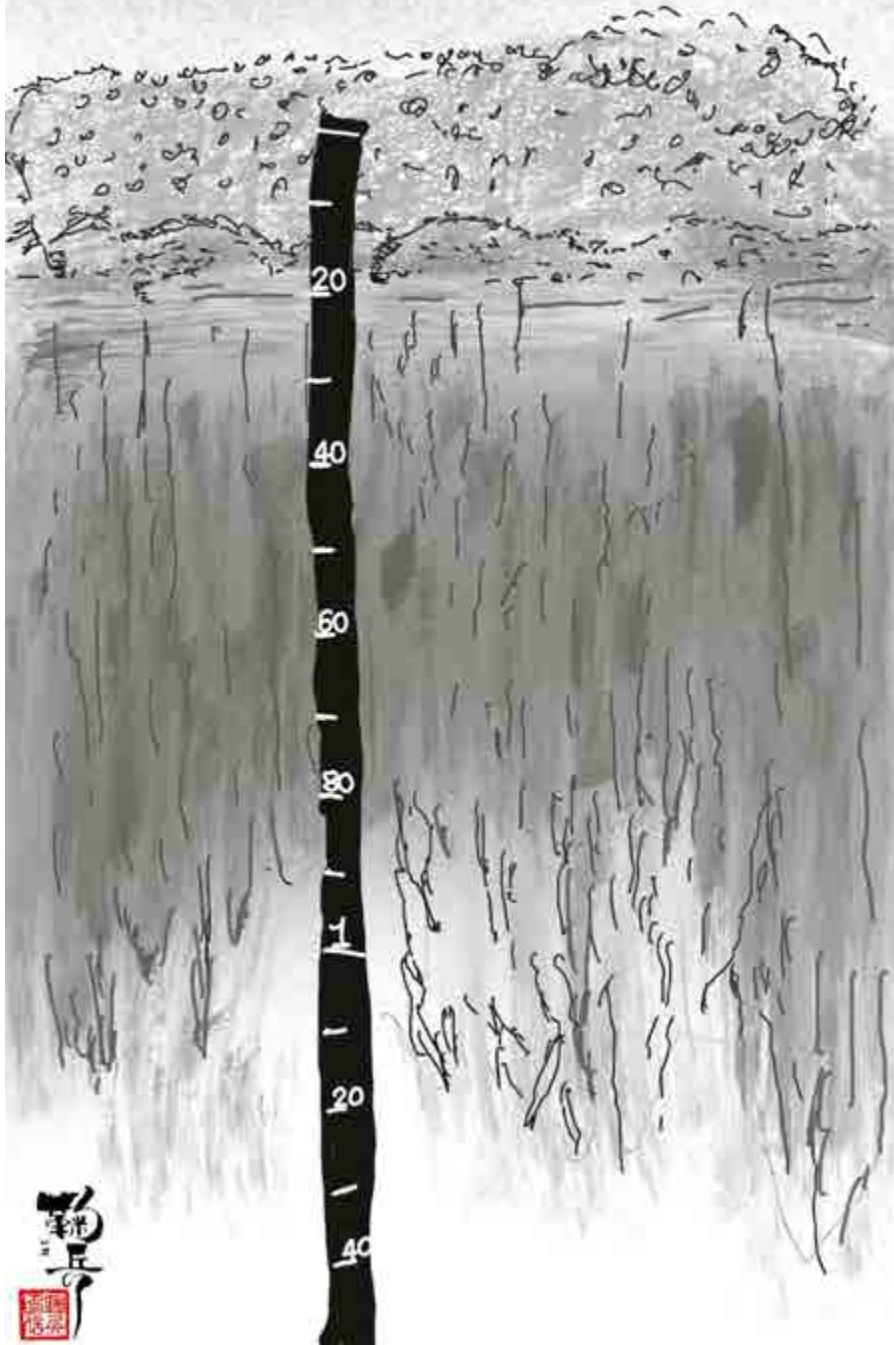


Figure 1.1c Artistic representation (drawing) of a Phaeozem profile in Heilongjiang province, China

1 | Black soils and the post-2020 Global Biodiversity Framework



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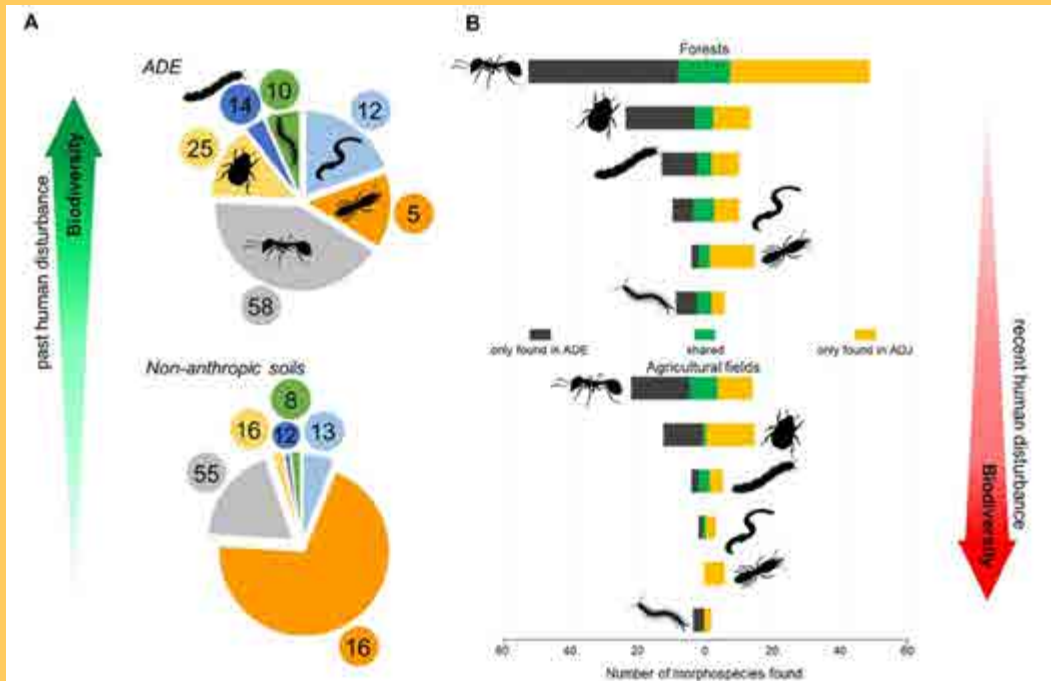
Maize cropping system on black soils, Beian County, China.

According to FAO (2022) and Hou (2022), China has the third largest area of black soils. Between 1996–2019, more than 11 million hectares of black soils were converted to crop-growing. Land use change and agricultural intensification is causing ecosystem degradation such as soil erosion, pollution (by pesticides and heavy metals), depletion of groundwater, and reduction of wetland habitats. In this context, in August 2022, the National People’s Congress of China enacted a law for the protection of black soils, considering their valuable attributes as fertile soils (high organic matter content), their fundamental role for food security, and the potential of soil organisms to provide healthy soils for sustainable development of agriculture in black soil regions. Hence it is very important to input specific requirements into the new law for the monitoring and protection of soil biodiversity, in order to align to the post-2020 Global Biodiversity Framework (under discussion) at the upcoming United Nations Biodiversity Conference, in Kunming, China (COP-15).

Source: Hou, D. 2022. *China: protect black soil for biodiversity*. *Nature*, 604(7904): 40–40. <https://doi.org/10.1038/d41586-022-00942-6>



2 | Soil biodiversity in the Amazonian Dark Earths



Macroinvertebrate populations in Amazonian Dark Earths (ADE) and non-anthropogenic soils (ADJ). A) Relative density and number of morphospecies of most abundant macrofauna taxa in forest sites in ADE and ADJ soils. B) Number of morphospecies of the most abundant taxa in ADE and ADJ soils.

Information about soil biodiversity in Amazonian Dark Earths is very scarce, especially on soil macroinvertebrates, with only two studies published on soil macrofauna (Cunha *et al.*, 2016; Demetrio *et al.*, 2021); with both studies being part of the same project. Based in these data, ADEs seem to host an invertebrate community different from those found in adjacent soil (non-anthropogenic soils). Observing the relative density of the most abundant macrofauna taxa in ADEs and ADJ soils, it is easy to observe that termites dominate the soil macrofauna abundance in ADJ, while in ADEs the taxa density is more even (see Figure A, above). Although the number of morphospecies occurring in ADEs is quite similar to those in ADJ soils (excepting for some taxa), most of these morphospecies are found exclusively in ADE sites, indicating probably that ADEs are a habitat that allows the development of species that are less abundant (rare) in ADJ soils. However, while the past human disturbance which formed the ADEs seems to be positive for macroinvertebrate populations, recent human disturbance (e.g. livestock and intensive modern agriculture) affect negatively macrofauna diversity in ADEs (See Figure B, above).

Source: Cunha, L., Brown, G.G., Stanton, D.W.G., Da Silva, E., Hansel, F.A., Jorge, G., McKey, D., Vidal-Torrado, P., Macedo, R., Velasquez, E., James, S., Samuel, W. & Lavelle, P.K. 2016. *Soil animals and pedogenesis: the role of earthworms in anthropogenic soils*. Soil Science, 181(3-4): 110-125. <https://doi.org/10.1097/SS.0000000000000144>

3 | V.V. Alekhin central-Chernozem Biosphere State Reserve



Meadow steppe, central-Chernozem Biosphere State Reserve, Russian Federation

The V.V. Alekhin Central-Chernozem Biosphere State Reserve (Central Black soil Reserve) is located in the Kursk region of the Russian Federation. The Russian Federation has the largest area of black soils (3 268 million hectares) (FAO,2022). According to the Ministry of Natural Resources and Environment of the Russian Federation (2022) the reserve was created in 1935, and has a total area of 5 287 hectares, but their black soils have been studied since 1932. Black soils have high organic carbon content and high fertility that are usually used for food production. Chernozem soils are one of the most fertile soils used in agricultural production. The Chernozem soils of the reserve have a high humus content (9 to 13 percent) in the upper 10 cm of soil and a thickness of the humus horizon thickness of 1.5 metres. These soils were formed under the influence of the meadow steppe vegetation, which is the main type of vegetation in the Reserve together with the forest (oak, pine and poplar). Forest-steppe Chernozems are the richest soils in microorganisms in temperate climates. This reserve has a biodiversity of 7 200 species of living organisms. One thousand are fungi, and about 4 000 are insects (Coleoptera, Diptera, Hymenoptera) of which 1 000 species of beetles have been identified and 191 species of spiders have also been found. Bearing in mind that the Central Black Soil Reserve is considered similar to prehistoric steppes, it can serve as a reference site to monitor soil health (soil fertility, carbon sequestration, biodiversity, GHG emissions, etc.) and contribute to environmental impact assessments (EIA) on black soil ecosystems. As soil scientist Vasily Vasilyevich Dokuchaev wrote:

“As you know, our Russian chernozem steppes, by the nature of climate, terrain, vegetation and animals, and partly also by the land and soils, are an inseparable part of that great steppe belt, which almost completely surrounds the entire northern hemisphere...”



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Vermic Chernozem



Photo 1.1 Black soil (Luvic Phaeozems) region in the Altai Mountains, southern Siberia, Russian Federation

1.2 Global perspectives and challenges

The Status of the World's Soil Resources Report (FAO and ITPS, 2015) defined the ten threats at a global scale to soil functions, highlighting soil erosion, SOC loss and nutrient imbalance as the top three. Because of land use change (from natural grasslands to cropping systems), unsustainable management practices and excessive use of agrochemicals, most of the black soils have already lost at least half of their carbon stocks and suffer from moderate to severe erosion processes, as well as nutrient imbalances, acidification, compaction and soil biodiversity loss (FAO and ITPS, 2015).

For centuries, black soils have been cultivated in the black earth belts in Eurasia and North America. Due to intensive cultivation systems (mainly cereals, oilseeds, and pastures), land use change and excessive use of fertilizers, black soils have lost 20 to 50 percent of their original SOC stock (Iutynskaya and Patyka, 2010; Krupenikov, 1992; Ciolacu, 2017; Agriculture and Agri-Food Canada, 2003; Durán, 2010; Baethgen and Morón, 2000), with the carbon being released into the atmosphere mostly in CO₂ and exacerbating global warming. According to Lal (2021), Chernozems soils have a global impact on climate change adaptation and mitigation, as they can annually sequester 0.7 to 1.5 MgC/ha through sustainable soil management practices, thus reducing global GHGs emissions.

Even though climatic conditions are generally favourable in most of black soil regions, predicted climate variability (which increases climate change) will also pose a considerable risk to global agriculture.

Apart from SOC losses, black soils are threatened by soil erosion (a widespread phenomenon that severely decreases soil health in sloping areas), unsustainable practices caused by fallow systems, excessive fertilization, monocultures, irrigation, ploughing, among others, that can produce the loss of huge amounts of soil. For example, it has been estimated that Ukraine lost 500 million tonnes of soil per year due to erosion, equivalent to a loss of USD 5 billion per year in nutrients (Fileccia *et al.*, 2014).

In terms of agrifood production, the ongoing military conflict in Eurasia poses a major challenge to world

food production. During the 169th session of the FAO Council, the ongoing conflicts were discussed in the context of food insecurity. The Russian Federation and Ukraine (black soil countries) together account for almost 30 percent of global wheat exports and about 80 percent of sunflower exports, as well as the Russian Federation being the largest exporter of fertilizers. This means that supply disruption will also affect global agrifood systems, impacting consumers worldwide and increasing food, energy and fertilizer prices. War conflicts also contribute to the degradation of black soils, polluting them with various sources of contaminants (heavy metals, depleted uranium, napalm, etc.), and greatly reducing their biodiversity (FAO and UNEP, 2021).



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4 | Black soils and food security hazards

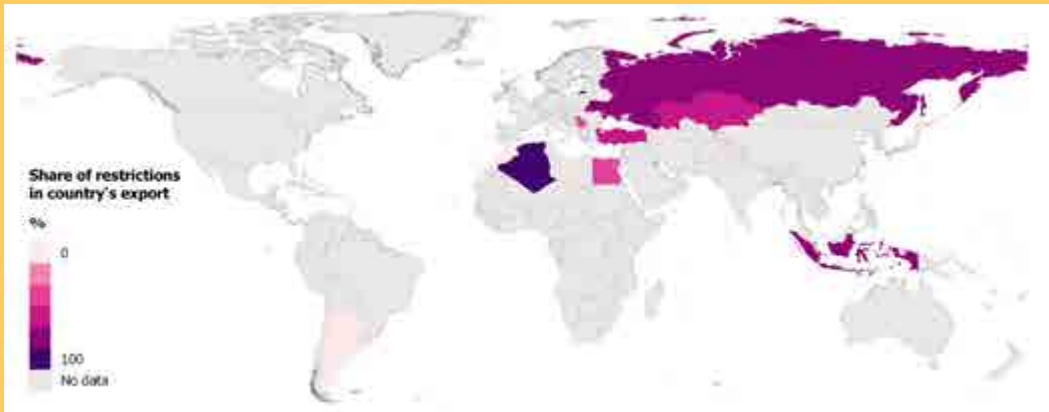


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Rice cropping system on black soils, Jiusan farm, China.

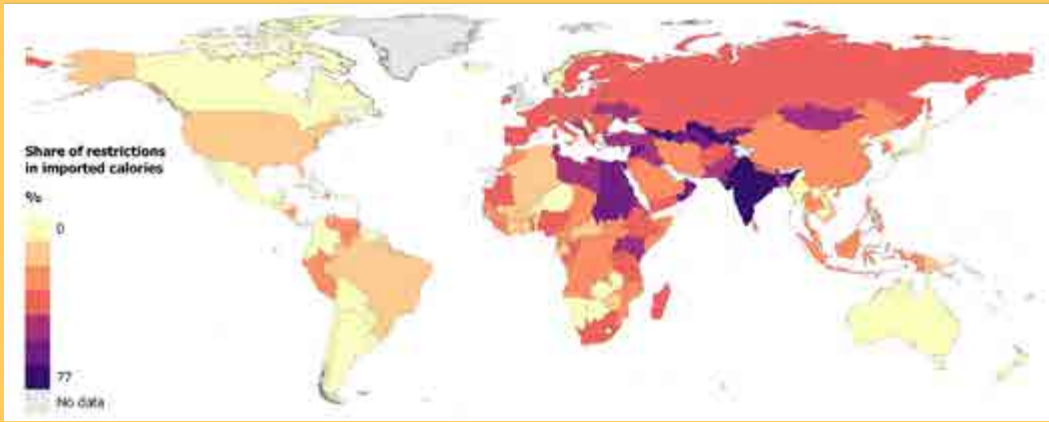
Soil is an essential resource and a vital part of the natural environment from which 95 percent of the global food is produced (FAO, 2015). However, 33 percent of the Earth's soils are degraded, mostly due to erosion, SOC loss, compaction, salinization and sodification, acidification, and pollution (FAO and ITPS, 2015). SOC loss is of special importance since black soils are considered amongst the most fertile soils due to their high organic matter content. On the other hand, the current war situation in Eurasia constitutes a new threat to black soils, especially to agricultural production and global food security. The Russian Federation and Ukraine have some of the most fertile soils in the world, with 326 and 34 million hectares of black soils respectively (FAO, 2022). In Ukraine, 68 percent of the arable land has Chernozem soils, followed by Phaeozems and Albeluvisols (Fileccia *et al.*, 2014). Countries such as Armenia, Georgia, Kazakhstan, Türkiye, and regions such as the Near East and North Africa, rely on imports of wheat and other commodities from the Russian Federation and Ukraine (World Bank, 2022). The impact of the war on the global economy is causing higher prices for commodities (World Bank, 2022). Exports of nitrogenous fertilizers have also decreased as a result of the war. The Russian Federation is the world's largest exporter of fertilizer, with 13 percent of global exports and is also a major supplier of natural gas (World Bank, 2022). Supply shortages and higher prices of food threatens world food security, as well as from destroying agricultural and civilian infrastructure.

5 | The vulnerability of global food markets



Impact of restrictions of food exporters.

Modified to comply with UN. 2020. Map of the World. <https://www.un.org/geospatial/file/3420>



Cumulative effects since early 2022 on the impact of restrictions of food importers

Modified to comply with UN. 2020. Map of the World. <https://www.un.org/geospatial/file/3420>

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

World food markets are vulnerable to the effects of the COVID-19 pandemic, global climate change, and conflicts. Glauber *et al.*, (2022) estimated the effects of the Russian Federation and Ukrainian war on food export restrictions, using the International Food Policy Research Institute (IFPRI) Food and Fertilizer Export Restrictions Tracker. This tool tracks the share of restricted exports in terms of kilocalories and USD. 17 percent of the total calories traded in the world are affected by the restrictions. Ukraine, the Russian Federation, Indonesia, Argentina, Türkiye, Kyrgyzstan and Kazakhstan have applied mainly export restrictions on cereals (wheat, corn) and palm, sunflower and soybean (see map above). The importing countries of these products such as Central Asian Countries (Mongolia), North African (Egypt and the Sudan), India, Pakistan and Bangladesh have been affected by the restrictions (see map above). Rising food prices, as well as an increase in the number of other exporting countries imposing their own restrictions, are some of the consequences of commodity export restrictions that threaten global food security. Ukraine is one of the main contributors to world food security through wheat exports and however, according to Smith (2022), some of its most productive agricultural lands will be vulnerable due to the current situation. Ukraine is one of ten countries with the largest area of black soils, representing 68 percent of its arable land (Fileccia *et al.*, 2014).

Source: Glauber, J., Laborde, D. & Mamun, A. 2022. *From bad to worse: How Russia-Ukraine war-related export restrictions exacerbate global food insecurity*. IFPRI blog series: high food/fertiliser prices and war in Ukraine.

1.3 A growing awareness of the importance of black soils

One of the main recommendations from the Global Symposium on Soil Organic Carbon (GSOC17) was to prioritize soils with the largest SOC reserves and promote the development of national and regional soil conservation policies to curb SOC losses.

In this context, the [*International Network of Black Soils*](#) (INBS) was established in March 2017 during the GSOC17 with the main purpose to promote the conservation and sustainable management of world's black soils. Since then, a series of working sessions and workshops were organized to agree on the definition of black soils and provide a platform for member countries to discuss common problems, and research gaps in the conservation, sustainable management, assessment and monitoring of black soils. During the [*International Symposium on Black Soils*](#) (ISBS18), which took place in Harbin, China on September 2018, delegates from 18 black soil countries and members of the INBS signed the [*Harbin communiqué*](#), an agreement to advance in science and technology of black soil management in the world. The INBS is currently composed of 31 countries from all black soil regions of the world.

The recently launched [*Global Black Soil Distribution Map*](#) (GBSmap) is a country-driven approach based on the endorsed definition of black soils, led by the FAO's Global Soil Partnership, with the participation of 31

black soil countries. The GBSmap is a valuable tool that not only provides information on the distribution of black soils, but also key information on their relevance for food security, sustainable development, and climate change mitigation and adaptation (FAO, 2022). The GBSmap is a living product that provides decision makers with robust data that can be translated into better decision making.

The INBS agreed to prepare the Global Status of Black Soils report, following an inclusive approach bringing together more than 188 soil scientists from 31 countries to understand the status and challenges of black soils and plan its management, conservation, and monitoring. This global report is based mainly on the contributions of INBS member countries, which have provided accurate information that will allow us to have a better understanding and knowledge of black soils.

The intention of this global report is, first, to raise awareness on the importance of this limited natural resource (black soils); second, to understand black soils' distribution and status in a complex context of environmental degradation, climate change, food insecurity, global socio-political problems and pandemics; and finally, to provide key information that will give decision makers the necessary tools to curb degradation and promote the sustainable use, management and conservation of this black treasure.





2. Global distribution and characteristics of black soils

2.1 Definition of black soils

Although “black soils” is a term used in some national soil classifications, which is influenced by the national linguistic specifics, there has been no consistent definition for black soils at the global level. In the WRB classification (IUSS Working Group WRB, 2015), the majority of black soils would correspond to Chernozems, Kastanozems and Phaeozems. However, other groups such as Vertisols, Fluvisols, Cambisols and Anthrosols may fit the definition of black soils. In the United States of America and Argentina, black soils correspond to the Mollisols Great Order according to the United States of America Soil Taxonomy (USDA, 2014). Many other regional variants exist, such as in China, where the original name for these soils was “black soils”, and they are now classified as “Isohumisols” in Chinese Soil Taxonomy. In Ukraine, these soil types are included in a group characterized a humus-accumulative type of soil formation, which is a great group of the Chernozems, assimilated to Russian Federation black soils or “black earths”.

The harmonization of the definition of black soils is required to facilitate their sustainable management and international technical exchanges. In 2019, FAO and its advisory body, the Intergovernmental Technical Panel on Soils (ITPS), endorsed the definition of black

soils as “black soils are mineral soils which have a black surface horizon, enriched with organic carbon that is at least 25 cm deep” (FAO, 2019).

Two categories of black soils (1st and 2nd categories) are recognized. The categories are distinguished to recognize the higher value, and thus greater need for protection, of some soils (Category 1), while still including a wider range of soils within the overall black soil definition (Category 2).

The 1st category of black soils (the most vulnerable and endangered, needing the highest rate of protection at a global level) are those having all five properties given below:

1. The presence of black or very dark surface horizons typically with a chroma of ≤ 3 moist, a value of ≤ 3 moist and ≤ 5 dry (by Munsell colours);
2. The total thickness of black surface horizons ≥ 25 cm;
3. Organic carbon content in the upper 25 cm of the black horizons of ≥ 1.2 percent (or ≥ 0.6 percent for tropical regions) and ≤ 20 percent;
4. Cation-exchange capacity (CEC) in the black surface horizons ≥ 25 cmol/kg; and
5. A base saturation in the black surface horizons ≥ 50 percent.

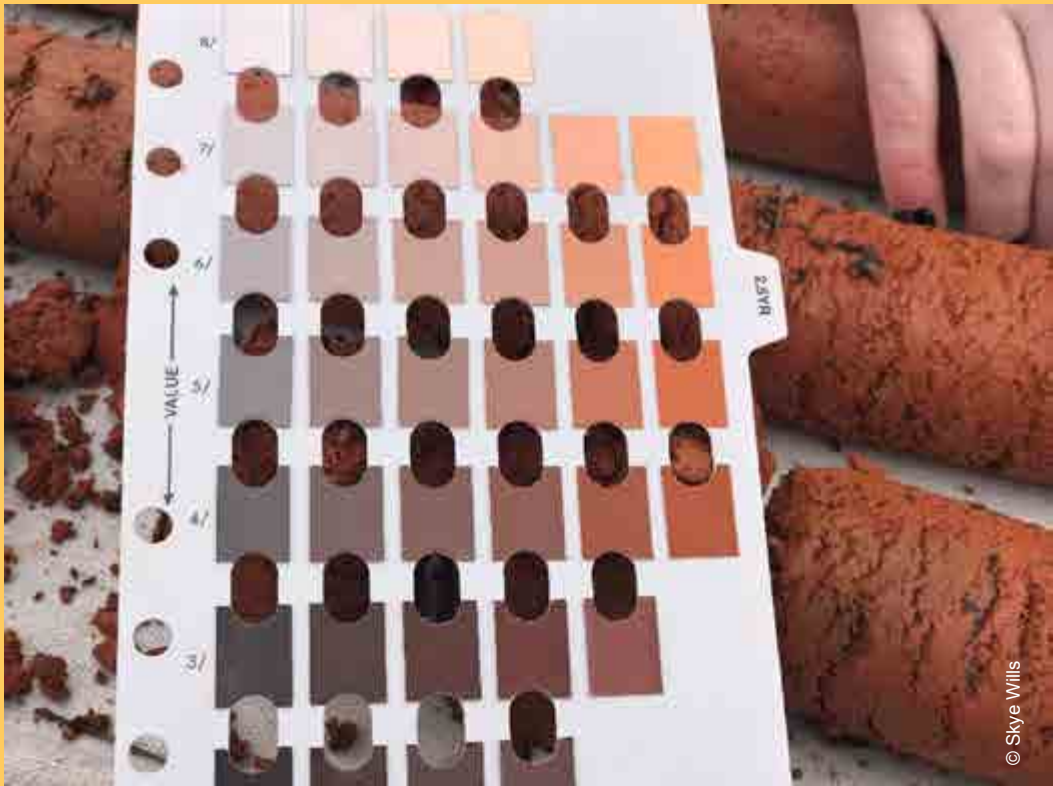
Most, but not all, 1st category black soils have a well-developed granular or fine sub-angular structure and high aggregate stability in the black surface horizons that are in a non or slightly degraded state, or in the humus-rich underlying horizon which has not been subjected to degradation.

The 2nd category of black soils (mostly endangered at the national level) are those having all three properties given below:

1. The presence of black or very dark surface horizons typically with a chroma of ≤ 3 moist, a value of ≤ 3 moist and ≤ 5 dry (by Munsell colours);
2. The total thickness of the black surface horizons of ≥ 25 cm; and
3. Organic carbon content in the upper 25 cm of the black horizons ≥ 1.2 percent (or ≥ 0.6 percent for tropical regions) and ≤ 20 percent.



6 | Global Soil Doctors Programme



Impact of restrictions of food exporters

Adapted figure from Food and Fertilizer Export Restrictions Tracker by David Laborde (2022)

Soil colour is a very useful indicator of soil quality because it can provide an indirect measure of other soil properties, such as organic matter content. Generally, black soils are associated with a high organic matter content which is what gives soils their dark colour. These soils are rich in organic carbon (0.6 to 20 percent) in the upper 25 cm of the black horizons (FAO, 2019). The most commonly used method to determine the colour of soils is through the Munsell Table. It classifies soils based on three attributes: hue (the dominant colour of the soil), value (the lightness or darkness of the soil colour), and chroma (the intensity or saturation of the colour) (Zhang *et al.*, 2021b). For example, the presence of black or very dark surface horizons is typically found with a chroma of ≤ 3 wet, a value of ≤ 3 wet and ≤ 5 dry (according to Munsell colours) (FAO, 2019). Another method for assessing soil colour is found in the FAO Global Soil Doctors Programme's "Methods of Soil Analysis" document (FAO, 2020). This document contains a list of easy-to-use, low-cost soil testing methods that can help assess soil condition directly in the field. The method consists of: 1) sampling: one sample from the field, the second under the nearest fence or similar protected or undisturbed area; and 2) comparison: the relative difference in colour of the soil samples to identify the relative change in soil colour that has occurred.

2.2 Creation of a global map of black soils

Digital soil mapping (DSM) is the computer-assisted production of digital maps of soil type and soil properties by use of mathematical and statistical models that combine information from soil observations with information contained in explanatory environmental

variables. DSM has been largely applied to predict the distribution of soil types (Chaney *et al.*, 2016; Holmes *et al.*, 2015; Nauman and Thompson, 2014; Bui and Moran, 2001). The advantages of DSM with respect to alternative methods are that the mapping process can be documented, it can be easily modified and updated if necessary, and the prediction uncertainty can be estimated.



In the process of creating the global map of black soils, every country member was responsible for producing its own black soil map and a bottom-up, country-driven approach was followed to define the global coverage of black soils. A similar experience was successfully implemented for the Global Soil Organic Carbon map (GSOCmap) done by FAO (FAO, 2017), and therefore, a similar approach was implemented in this case.

The goals of this section are to describe the DSM approach implemented for mapping black soils at country level and summarize black soil products of member countries. Some countries could not follow

the methodology proposed due to a lack of up-to-date verified soil survey samples to cover the whole country territory, and instead they have presented a first version of what they considered to be the area covered by black soils.

2.2.1 Data collection process

The 2nd category black soils for mapping purposes were used for the global map. In order to map their distribution, a digital soil mapping framework was applied (Figure 2.1).

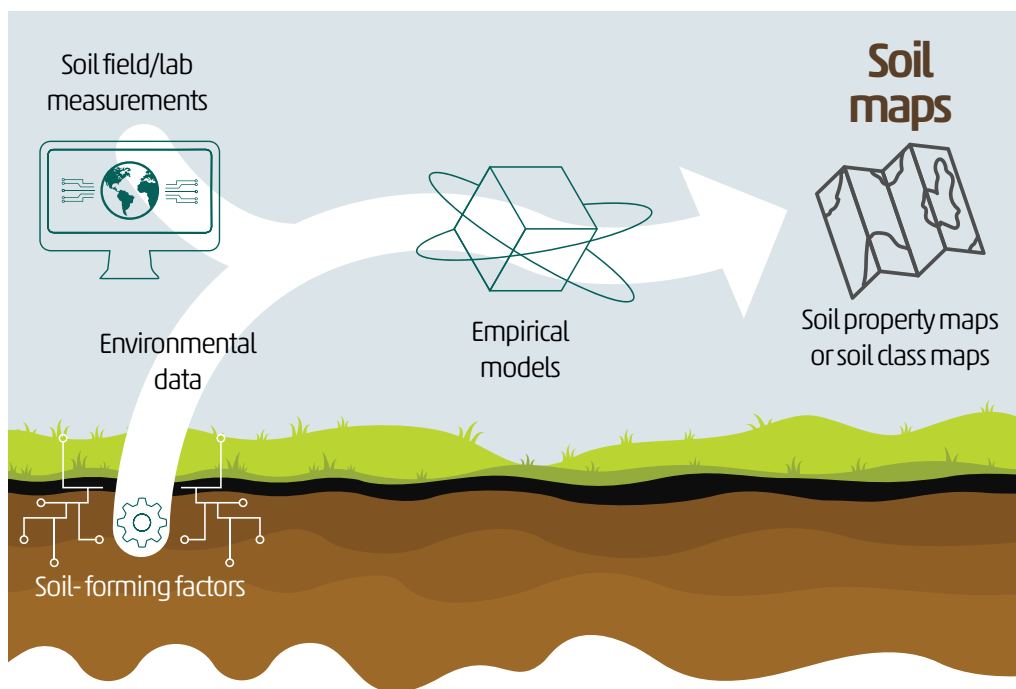


Figure 2.1 General framework of digital soil mapping (DSM)

Source: Authors' own elaboration

In DSM, soil data from lab measurements and field observations were combined with environmental data through empirical predictive models to spatially interpolate target soil properties and soil classes. Ideally, soil data is available at point locations. When this is not the case, classical polygon-based soil maps can be used as an information source. Additional environmental data are also used, which are meant to represent or to be proxies of soil-forming factor, and helping to represent the spatial variation of the target soil property. This additional data usually includes terrain attributes, such as digital elevation models, slope, terrain curvature, etc., remote sensing data from different missions, such as Landsat, Sentinel, MODIS, etc., climate data (locally

or globally available), as well as other maps, such as legacy soil maps, geological maps, and land use maps, etc. With regards to empirical models, there are a wide range of options depending on the nature of our target variable(s) (qualitative or quantitative) and the type of product that we want to obtain. Nowadays, one of the most common methods applied in DSM is Random Forest (Breiman, 2001), as well as many other machine learning algorithms (Hothorn, 2022). The resulting soil maps are generally raster maps of the most probable soil property value or soil class together along with an uncertainty map that indicates the level of confidence of the primary product.

2.2.2 National maps

Figure 2.2 shows the workflow for mapping the distribution of black soils at country level using the

DSM approach. For this case, we assume that soil profiles with geographical coordinates are available in the study area.

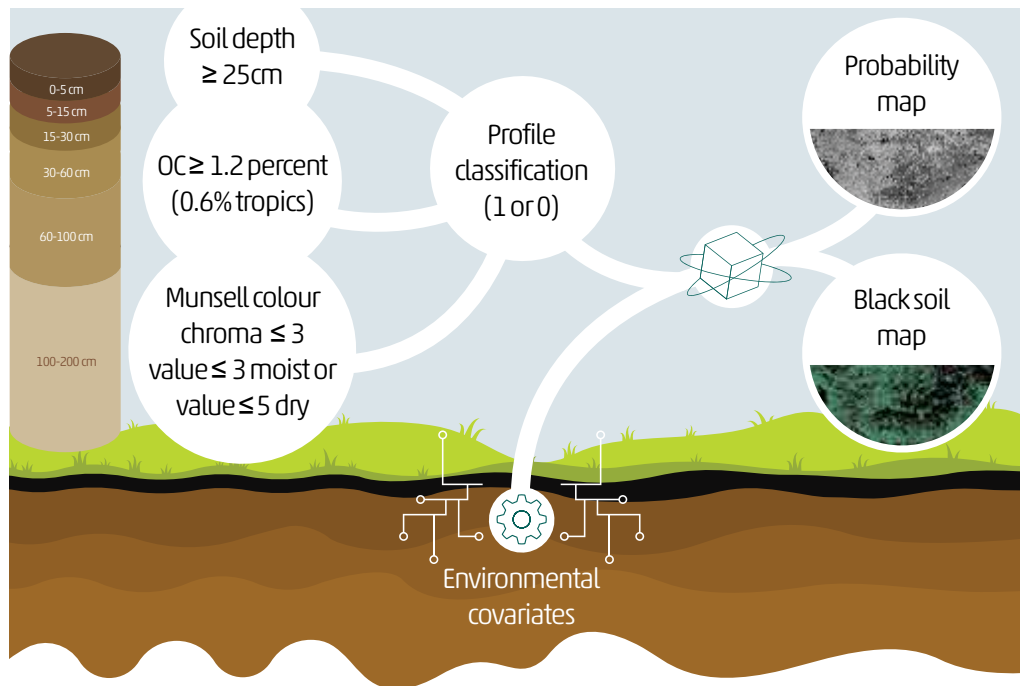


Figure 2.2 Workflow for mapping black soils

Source: Authors' own elaboration

First, we classified the soil profiles into black soils (1) or non-black soils (0) based on the soil horizons/layers to 25 cm depth. Black soils had Munsell colours of these horizons that had chromas ≤ 3 and values ≤ 3 moist or value ≤ 5 dry. These horizons in black soils also had to have concentrations of organic carbon higher or equal to 1.2 percent (0.6 percent OC in tropical soils). If a profile was within these thresholds, then it was classified as a black soil (1), otherwise it was a non-black soil (0). Second, we prepared environmental covariates that covered the whole study area (or country). Environmental covariates included climate data, vegetation data, and terrain attributes. Other covariates, such as national geology maps and soil maps, etc., could be included. A rich source of covariates is the OpenLandMap project (OpenLandMap/global-layers, 2022). Third, we applied a Random Forest model. Random Forests is a regression and classification decision tree approach widely used in DSM. Random forests include hyper parameters that must be

optimized before calibration. Accuracy was measured using 20 times 10-fold cross-validation and confusion matrices. Overall accuracy and class-accuracy were reported. Finally, the model was used for prediction at 1 km resolution. Both the probability map and the categorical map of the black soil distribution were generated (OpenLandMap/global-layers, 2022).

Some countries were not able to follow the proposed methodology because of a lack of data, and instead provided polygon-based soil maps where black soils were present, based on the large scale soil survey or expert knowledge. This is the case for Bulgaria, Slovakia and Indonesia. The Russian Federation provided a polygon map with expert knowledge input where they indicated the probability of having black soils at each cartographic unit. Thailand and the Syrian Arab Republic also provided polygon maps, but we did not include them within the global map because the scales were too small.

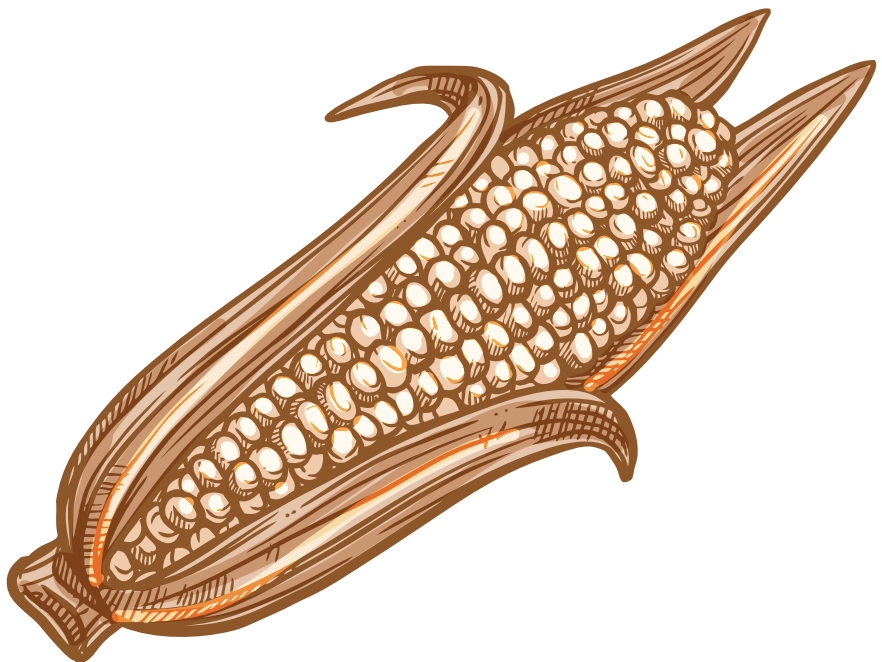
2.3 Global map of black soils

National maps of black soils provided by the country members were used to extrapolate probability values at global scale. A total of 30 000 random locations were allocated spatially based on three main thresholds: 1) 10 000 samples were randomly distributed on pixels with probability less than 0.2; 2) another 10 000 samples were equally distributed along pixels with probability between 0.2 and 0.7; and 3) and another 10 000 samples were randomly distributed on pixels with probability greater than 0.7. Next, we gathered 41 globally explicit and openly available environmental variables. The majority of them came from OpenLandMap project (OpenLandMap/global-layers, 2022), including the probability of USDA soil orders (Mollisols, Vertisols, and Andosols), clay percentage map at 10 cm depth, pH map at 10 cm depth, snow coverage, monthly maximum temperatures, mean annual precipitation, cropland area, terrain attributes (slope and wetness index, among others), and land cover. Other sources of variables were Google Earth Engine, from which seasonal land surface temperature mean and standard deviation were extracted; the same method was applied to NDVI; and elevation at 1 km resolution was estimated using MERIT DEM.

A random forest model using recursive feature elimination was trained and used for prediction. Among the most important predictors were GSOCmap, terrain wetness index, land surface temperature, NDVI, clay percentage at 10 cm, precipitation, and maximum temperature. Detailed information about the methodology and results will be provided in the forthcoming GBSmap technical report.

The country maps that were used to produce the global map were of two types: probability maps (Argentina, Brazil, China, Colombia, Uruguay, Mexico, United States of America, Canada, Ukraine, and Poland) or detailed polygon maps (Bulgaria, Slovakia, Indonesia, and the Russian Federation)

The global map that resulted from this process is the first to give a global overview of the distribution of black soils (Figure 2.3). Black soils are found mostly in eastern Europe, central and eastern Asia, and the northern and southern hemispheres of the Americas. Table 2.1 depicts the top ten countries in terms of black soil areas, which together account for 93.4 percent of the total black soil area. The overall area of black soils is 725 million hectares, with the Russian Federation, Kazakhstan, and China accounting for more than half of it. The Russian Federation has by far the largest black soil area, with 327 million hectares accounting for 45 percent of the overall black soil area.



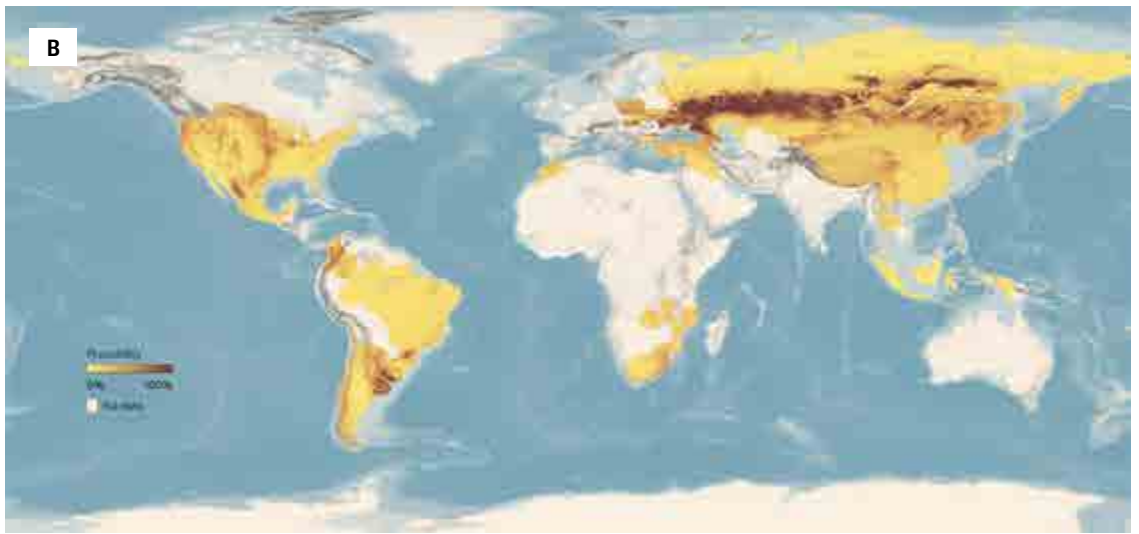


Figure 2.3 Global Black Soil Distribution map (GBSmap)

(A) categorical map showing areas with more than 50 percent probability of being black soils;

(B) continuous map showing the probability distribution of soils being black soils

Source: Authors' own elaboration

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.



Table 2.1 Top ten countries with the largest black soil areas

Country	Black soil area (million hectare)	Country area (million hectare)	Black soil proportion (percentage)
Russian Federation	326.8	1700.2	19.22
Kazakhstan	107.7	283.9	37.93
China	50	934.6	5.35
Argentina	39.7	278.1	14.28
Mongolia	38.6	156.5	24.67
Ukraine	34.2	60	57.01
United States of America	31.2	950.1	3.28
Colombia	24.5	113.8	21.54
Canada	13	997.5	1.30
Mexico	11.9	196.4	6.04

Source: Authors' own elaboration

2.3.1 Human use of black soils

We can assess population distribution in black soil areas using the gridded population of the world map (CIESIN, 2018) (Table 2.2). According to this, the Russian Federation has the largest number of individuals living on black soils (68 million inhabitants). Kazakhstan has the second largest area of black soils in the world, with

about 108 million hectares, yet it is modest in terms of its population (8 million people). With about 30 million people, China and Colombia are the countries with the second-largest populations living on black soils. While this is a minor percentage of China's population, 32 million people is an important proportion for Colombia (almost 50 percent of its population).

Table 2.2 Land cover and population in black soils

	Black soils	World	Percentage
Area (million hectare)	725	12 995	5.58
Cropland (million hectare)	227	1 308	17.36
Forest (million hectare)	212	4 496	4.72
Grassland (million hectare)	267	3 129	8.52
Population (million people)	223	7 788	2.86

Source: Authors' own elaboration

According to the land cover distribution, black soils are covered by 227 million hectares of cropland, 267 million hectares of grasslands and 212 million hectares of forests at global level. Black soils cover 5.6 percent of the global land area, are home to 2.86 percent of the global population, and have 17.36 percent of cropland, 8.05 percent of global SOC stock and 30.06 percent SOC stock of global cropland. These proportions, however vary between FAO regions (for example, Asia has approximately 50 percent black soils under grasslands, and North America has 54 percent of black soils that are under cropland).

At a global level, approximately one third of the black soil area is used as croplands, which represents 17.4 percent of the global croplands (Zanaga *et al.*, 2021). The distribution varies within each region.

From the total cropland in black soils, Europe and Eurasia account for 70 percent, while North America, Latin America and Caribbean, and Asia share ten percent each. This is of great significance for European and Eurasian agriculture, which represents 160 million hectares.

Despite representing a small portion of the world's soils, black soils feed the global population. They not only sustain people settled on them but also the rest of the world through exports. Key for food security and the global economy, a significant share of oilseed, cereal,

and tuber crops is cultivated in black soils. Globally, in 2010, 66 percent of sunflower seeds, 30 percent of wheat and 26 percent of potato outputs were harvested from black soils (Figure 2.4).

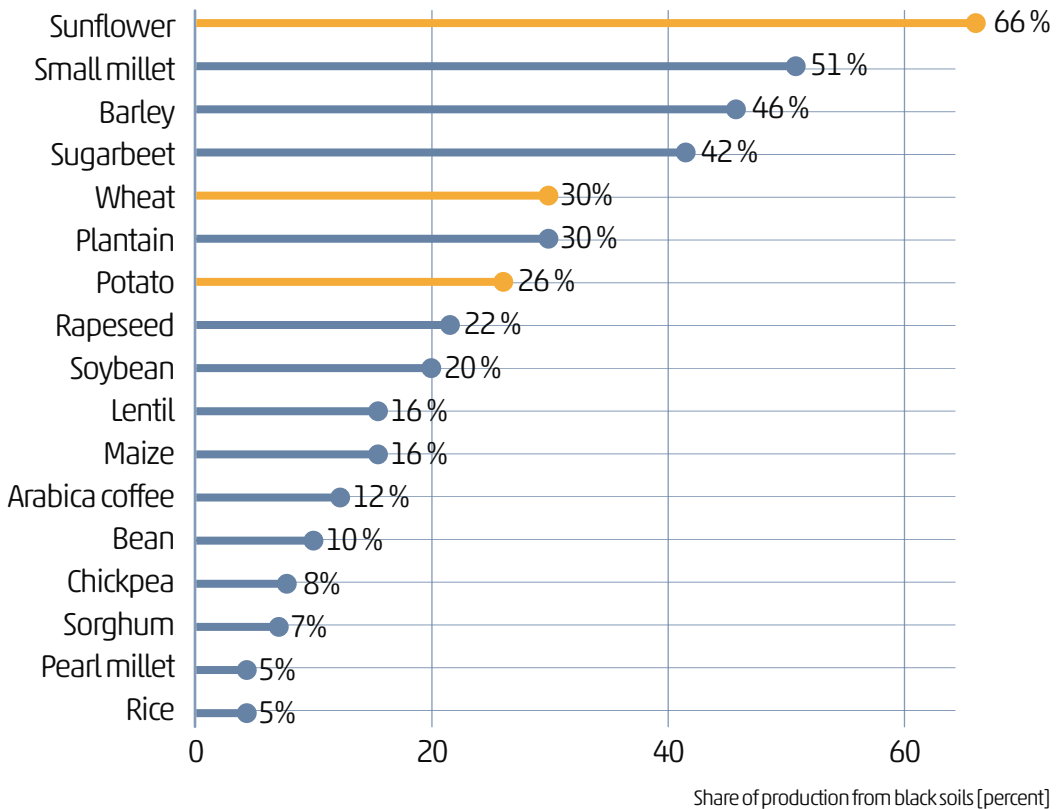


Figure 2.4 Global share of crop production directly attributable to black soils

The shares were derived by intersecting the GBSmap with the "Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0", International Food Policy Research Institute, 2019. Results for crop shares under 5 percent and for aggregated crop types were excluded from the analysis. **Source:** Authors' own elaboration

According to the land cover map of the ESA WorldCover (Zanaga *et al.*, 2021), there are 212.3 million hectares of forested black soils, which is 4.7 percent of the world's forests. The Russian Federation is by a large margin the country with more forests in black soils, with 142.9 millions hectares, which representing 15 percent of the Russian Federation forest lands. Colombia (18.5 million ha), China (12.7 million hectares) and the United States of America (7.1 million hectares) have the next three highest percentages.

The updated version of Hansen Global Forest Change v1.9 (Hansen *et al.*, 2013) reported that the forest loss in black soils has been 27.9 million hectares between 2000 and 2021 (FAO, 2022a). Forest loss has occurred mainly in the Russian Federation (20 million ha), but other countries such as the United

States of America, Brazil and Argentina also registered important forest loss. The three countries account for 4.6 million hectares evenly distributed.

2.3.2 Soil organic carbon content of black soils

Soil organic carbon between 0 to 30 cm depth has been estimated at 677 Pg worldwide (Pg = 1 billion tonnes) (Table 2.3) (FAO, 2017). Nine percent of this total is in black soils. Note that about 23.9 percent of SOC stock of Europe is in black soils, 9.7 percent for Latin America and Caribbean, 3.9 percent for North America and 8.7 percent for Asia.

Table 2.3 Total and cropland soil organic carbon stocks and potential carbon sequestration rates associated with black soils

	Black soils	World	Percentage
SOC stock (PgC)*	56.0	677	8.21
Cropland SOC stock (PgC)**	18.89	62.8	30.06
Potential SOC sequestration (PgC/year)	0.029	0.290	10.11

Notes:

*GSOCmap (FAO, 2017)

** Based on WorldCover map (Zanaga *et al.*, 2021)

*** Based on GSOCseq product (FAO, 2022c), scenario of ten percent increase in C inputs

Source: Authors' own elaboration

Potential SOC sequestration differs significantly between countries. In Europe, most of the total SOC potential sequestration remains in black soils. The Russian Federation, Ukraine and Kazakhstan could capture about 14 million TnC/year in black soils.

In Argentina, Colombia and Uruguay, a large proportion of their potential SOC sequestration is in black soils. In Asia, Mongolia accounts for 80 percent of the total potential SOC sequestration in black soils, while the same ratio only reaches 10 percent in China (FAO, 2022a).

7 | Standard operating procedures to determine soil organic carbon



The Global Soil Laboratory Network (GLOSOLAN) was established in 2017 with the aim purpose to strengthen the capacity of laboratories in soil analysis and promote the harmonization of soil analytical data with the goal for soil information to be comparable and interpretable across laboratories, countries and regions (FAO,2022b). GLOSOLAN actually amounts for 700 labs worldwide, distributed in Regional Soil Laboratory Networks (RESOLANs) for Asia (SEALNET), Latin America (LATSOLAN), Africa (AFRILAB), the Pacific (ASPAC), Europe and Eurasia (EUROSOLAN) and the Near East and North Africa (NENALAB). As part of its main activities, GLOSOLAN developed globally harmonized standard operating procedures (SOPs) for known soil analysis methods. For example, the SOP to determine total carbon is the Dumas dry combustion method, and to quantify soil organic carbon (SOC), while the corresponding SOPs are the Walkley-Black method (titration and colourimetric method), and the Tyurin method (spectrophotometric method). Soil carbon is probably the most important component of soils, as it affects almost all soil properties. In black soils, SOC estimation represents a major indicator for their definition and for better understanding their health. Black soils contain 8.2 percent of the world’s SOC, and their potential SOC sequestration is 10 percent of the global potential (FAO, 2022a). It is important to have SOPs that help us ensure the replicability of a measurement and the accuracy and traceability of the data.

2.4 The nature of black soils

Black soils are present on all continents. Under its strict definition, black soils have developed preferentially on prairie vegetation with grasses. However, in its expanded definition, black soils appear with other types of vegetation, such as woodland and wetland. They even appear with parent materials with expandable clay minerals, giving rise to Vertisols.

Black soils are named for their colour, organizing in the process of melanization and accumulation of organic matter. This is often due to with a chemical medium rich in bases and with high biological activity. Despite their high original fertility, many black soils have lost it due to the high pressures of agricultural and pasture use.

The degradation suffered is generalized. The most identified processes have been erosion by water and wind, acidification, lack of plant nutrients and worsening of soil physical-hydraulic quality. Most of this degradation is reversible only with the adoption of good management practices. However, soil loss due to erosion is irreversible and affects millions of hectares in South America and China, among others.

The implementation of recovery or restoration practices depends a lot on the good governance of the soil and the availability of resources. This limits recovery practices such that they are not carried out in all the affected countries, but mostly in developed countries. The problem is that as most of the food insecurity occurs in the poorest countries, not in the developed countries with available resources for recovery. This is the main challenge for monitoring and management – not only of the black soils – but of all the productive soils of the world.

2.4.1 Black soils of midlatitude grasslands

The most abundant area of distribution of deep black soils is associated with the midlatitude grasslands, the areas where Chernozems, Phaeozems, and Kastanozems occur (note that throughout this chapter WRB taxonomic classes are used unless otherwise noted). Deep black soils are developed in temperate or subtropical climates where precipitation is distributed more or less equally throughout the year. The black colour is a result of an accumulation of organic matter originating from numerous dying roots of gramineous vegetation in a process known as melanization (Bockheim and Hartemink, 2017; Rubio, Lavado and Pereyra, 2019)

Black soils may also penetrate to more humid and cooler landscapes where grassland is interspersed with forests. These soils of steppes, prairies, and pampas are the most widespread archetype of black soils.

Black soils cross the Eurasian continent from Austria in the west to Manchuria in the east, mostly between the latitudes of 45 and 55 N under temperate steppe vegetation. In North America, due to the specific gradient of temperature and mean annual precipitation, black soils under grass vegetation (prairies) form a broad band crossing the continent diagonally from northeast Mexico to the southwestern part of Canada flatland. In South America, black soils occupy extensive areas in pampa in Argentina and Uruguay, forming under warmer and more humid conditions than in the northern hemisphere, although the biome is close in appearance and functioning to the more temperate steppes and prairies. Currently it is agreed that black soils under grasslands accumulate significant amounts of humified organic matter because of the peculiarity of the biological cycling in these biomes, where a



© Wilk Sampaio de Almeida

significant part of biomass is represented by easily decayed fine roots and soil biological activity is high.

Black soils of midlatitude grasslands are the most extensively cultivated soils in the world. In Europe, Asia and North America, a major part of these soils is used as arable land for producing wheat, corn and soybean. In South America, in contrast, the area with black soils is used for pastures and agriculture. In all the continents, practically the entire area is used for agriculture, and only minor nature protection areas have virgin black soils under natural grasslands.

Apart from being highly productive lands, the black soils of midlatitude grasslands are responsible for multiple ecosystem services such as water retention, maintaining biodiversity both of soil organisms of various sizes, and animals inhabiting tall grass ecosystems. Grassland black soils of grasslands are the most important pools

of carbon among the soils, although endangered by the processes of organic carbon loss due to the accelerated humus oxidation under cultivation. In many places, the loss of humus and nutrient mining are the most important threats to black soils because these soils are considered as highly fertile “by nature” and thus do not need application of organic and mineral fertilizers. The other common threat is soil compaction due to the use of heavy machinery and consequent water erosion of over-compacted soil. Wind erosion is also a big problem (such as the infamous dust storms in the 1930s that tremendously affected the Midwest of the United States of America and the problem in west Siberia and north Kazakhstan in the USSR during the development of virgin lands in 1950s). Currently, soil salinization is a growing problem, especially in irrigated areas in the most arid parts of the distribution of black soils.



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8 | Black soils in Ukraine



© Zalavskij Yurii

Black soils in forest steppe of Ukraine, Solovei Vadym

Black soils distributed on the territory of Ukraine include a group of soils in grassland. They have an important common feature which is a high content of organic matter, which led to the formation of saturated dark (from dark gray to black) topsoil. In the grassland, black soils are represented mainly by Haplic Chernozems, which are found on low-lying plateaus and high loess terraces. In the past, these areas were represented by steppe meadows and meadow steppes. The soil cover of the northern steppe is represented mainly by Haplic Chernozems, which were formed under the herbaceous-fescue-feathergrass steppes. The diversity of soils is associated with an increase in aridity in the subzone from north to south, which led to a decrease in the thickness of the humus layer, carbon content in the topsoil, depth of accumulation of carbonates, gypsum, and water-soluble salts. The southern steppe is dominated by Calcic Chernozems (Tonguic), formed under fescue-feather steppes in arid climates. The main component of the soil cover of the dry steppe are Kastanozems. In the Carpathians and the Crimean Mountains black soils occur sporadically, in the first tier of vertical zonation. Degradation of black soils in grassland is caused by unreasonable economic activity, especially in the context of global warming and under the influence of agrochemical pollution. As a result, most of the territory of black soils especially in grassland should grow environmentally friendly agricultural products (Boroday, 2019), which is of direct importance to society.

2.4.2 Black soils of floodplains and wetlands

Another widespread variety of black soils is represented by soils of floodplains and wetlands. On floodplains, the dark colour is due to excessive soil moisture that hinders mineralization of organic residues and to the continuous input of fine organic particles transported with water. In wetlands, the black colour of the topsoil layer reflects the presence of incompletely decomposed plant material under anoxic conditions. This black material has much in common with dispersed peat or mud. These black soils commonly have excessive moisture content that makes the management of such soils difficult, requiring drainage to be used in agriculture. However, it should be noted that the drainage of these soils threatens key ecosystem services, such as carbon stocks, biodiversity, and water filtering and quality (Wang *et al.*, 2015). These soils are classified mainly as Mollic Gleysols, and those soils formed on the floodplains and tidal marshes also may receive the qualifier Fluvic. If the percentage of organic material is high, such soils may be classified as Histic Gleysols, but the topsoil consists mainly of clayey mud rather than of recognizable plant debris. The exact area covered by wetland black soils is difficult to estimate, because these soils commonly do not cover extensive areas and thus seldom appear on small scale maps. The specific feature of these soils is that they are practically ubiquitous and may be found practically in every climatic zone, though most of them are typical for

humid and subhumid areas. Unlike these difficult-to-map wetland soils, in Argentina these black soils cover 12 million hectares in huge continuous flood plains also affected by salt and sodium excesses (Rubio, Lavado and Pereyra, 2019).

The black soils of floodplains and wetlands can support highly productive meadows. For example, in the northern taiga zone, such soils are the most important land resources for producing forage for livestock. Beyond feed production, wetland black soils are important habitats for maintaining biodiversity. The reduction of the wetland area is responsible for the loss of biodiversity of birds, mammals, insects and fish worldwide. The black soils of the floodplains commonly have good water-holding capacity and thus play an important role in water regulation and prevention of floods.

Carbon stock in wetland black soils vary in a wide range. In some of these soils humus penetrates to a depth of more than 1 metre, and the total carbon reserves may be even higher than in deep Chernozems (O'Donnell *et al.*, 2016). Due to reductive conditions, at least for some period of the year, these hydromorphous soils serve as a sink for atmospheric carbon. However, some of these soils may produce methane which is released into the atmosphere and has a negative impact on atmospheric greenhouse gases concentration. Draining of wetland black soils can provoke a dramatic loss of soil organic carbon and consequent discharge of climatically active gasses to the atmosphere.



© Xingzhu Ma

9 | Black soils in the Chinese wetlands



Intensive rice cropping system in Sanjiang plain of China, 2011

Rapid and periodic assessment of the impact of land cover changes on ecosystem services at regional level is essential to understanding services and [sustainability](#) of ecosystems in black soils. For example a quantification and assessment of the changes of multiple ecosystem services was conducted in the black soil wetland in Sanjiang plain of China throughout land cover changes over the period from 1992 to 2012. This region is important for its large area of natural wetlands and intensive agriculture. The result has confirmed trade-offs between ecosystem services and negative consequences to environment in this black soil region. The trade-offs were typically manifested by increased water yield and significantly increased [food production](#), which is in contrast with significant losses in ecosystem carbon stocks and suitable waterbird habitats, mainly due to the conversion of land cover from wetland to farmland. This finding implies that [land use planning](#) and policy making for this economically important black soil region should take ecosystem service losses into account in order to preserve its natural ecosystems in the best interest of society.

Swelling black soils are also an abundant soil group, which is widespread from tropics to temperate areas under alternating dry and wet conditions. Shrinkage of these soils in dry seasons and their swelling in the rainy season is due to their specific mineralogical composition of clays with the predominance of smectites. Most of these clayey soils are black, though the organic carbon content is not very high. Their dark appearance is due to the presence of humus-clay complexes that have grey to black colour. These soils are classified as Vertisols. These soils are well-known over the world and practically every traditional soil classification has a special name for such soils, reflecting their particular physical properties. The list of vernacular classification for compacted black soils includes almost 100 names worldwide (Krasilnikov *et al.*, 2009).

Swelling black soils are widespread in lowlands and valleys under the tropical and subtropical climates with contrasting dry and moist seasons. The most extensive areas may be found in Australia and India, with smaller areas on the plains around the Gulf of Mexico in North America and in Uruguay, Northeast Argentina and south

Brazil in South America. Minor areas may be found in temperate areas, including central, eastern and western Europe. Most of these soils form in lacustrine and marine sediments, but also in tropical areas there are Vertisols derived from smectite-rich products of basalt weathering. Also, in places Vertisols may form volcanic glass in toposequences together with Andosols.

Although hardening and cracking of Vertisols in dry seasons may cause problems in their management, these soils are considered to be productive in tropical and subtropical regions compared to strongly weathered Ferralsols and Acrisols. In India, their technical name in the nineteenth century was “black cotton soils” that indicating their importance for producing fibre.

Swelling black soils typically avoid water erosion because of their location in the lowlands. Their packed structure also prevents them from wind erosion. However, by nature these soils are vulnerable to shrinkage and cracking. Specific physical soil properties (swelling and cracking) cause troubles not only for their agricultural management, but also for road and civil engineering (Chen, 2012; Mokhtari and Dehghani, 2012).



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10 | Argentinian Vertisols



Native vegetation of the southern Mesopotamian region for low-input livestock production (Entre Ríos province, Argentina), and the corresponding soil profile (Hapludert)

In Argentina, swelling black soils (Vertisols), are found in various regions, but they are particularly relevant in the southern part of the Mesopotamian region, and in the eastern part of the Pampean region. Vertisols can also be found in restricted areas of the Argentine Chaco and the Patagonian region (Moretti *et al.*, 2019). The parent material of Vertisols of this region, as well as of associated vertic Luvisols and Phaeozems, is made up of sediments of silty-clay or clay-loam textures, with a predominance of smectites in its clay fraction and quartz in the coarse fraction, and with a considerable proportion of calcium carbonate, some gypsum and manganese and iron oxides segregations. These soils are mainly devoted to mixed crop-livestock production, though a small proportion is used to grow rice. In recent years, soybean growing has taken over these soils. Because of their low permeability, undulating relief, and summer rainstorms, these soils are prone to erosion. No-till and contour-line cultivation are now widely used to mitigate erosion problems (Cumba, Imbellone and Ligier, 2005; Bedendo, 2019). More information is in Annex I (Section A.4.1)

2.4.4 Volcanic black soils

Volcanic black soils are a less well understood group of soils where black colour does not correspond well with the current climatic conditions. Black soils on volcanic ash may be found both under grassland and forest vegetation. Recent studies disapproved the hypothesis that in the black colour reflects soil development under grasslands in the past (Sedov *et al.*, 2003). The intensive black colour is reflected in the name of these soils, Andosols (in Japanese An- means dark and Do- means soil). These soils are rich in humus, containing mainly humic acids, which are partly complexed with poorly ordered aluminosilicates, allophane and imogolite. Many volcanic soils are dark, except those on recent ash deposits or formed under a arid climate.

The distribution of these soils depends on recent volcanic activity and has little relation to current climates. Only in the coldest regions, where weathering

rate is exceptionally low, does volcanic glass not produce amorphous compounds essential for volcanic black soils formation. Most of these soils form in the mountains and in the mountain toeslopes. The most extensive areas of these soils are found in Japan, New Zealand, Iceland and Indonesia. In North America, such soils are found in the Rocky Mountains and Transmexican Volcanic Belt and in South America along the Andes. The productivity of these soils is relatively high, though specific P retention is a common limitation factor for their productivity. Apart from their use in agriculture, these soils contribute a lot to water retention because of their high water-holding capacity. The latter property also protects them from water erosion, though slope processes such as landslides are rather common. Carbon reserves may be high in volcanic soils, especially when pedocomplexes with multiple buried profiles form in the zones of active volcanism.

11 | The Japanese black soils



Andosols in Japan

Black soils in Japan are called “Kurobokudo”, which means black (kuro) and fluffy (boku) soil in Japanese. The black soils are mainly derived from volcanic ejecta or tephra, and the soils have unique properties such as being light, soft and fluffy, having a high humus content, and very high phosphorous-fixing capacity. According to the World Reference Base for Soil Resources, these soils are classified as Andosols, derived from “ando” which denotes black and dark soil in Japanese (Shoji *et al.*, 1993). Andosols have the largest distribution area among the soil great groups in Japan. The total distribution area of Andosols in Japan is estimated at some 0.1 million km², which is about 10 percent of the global Andosol distribution area. Andosols are mainly distributed in the southern part of Hokkaido, in the northeastern part of Tohoku, and in the Kanto-Koushinetsu and Kyushu regions (Saigusa, Matsuyama and Abe, 1992; Fujita *et al.*, 2007; Okuda *et al.*, 2007).

2.4.5 Black soils in tropics

Black soils are not very common in the tropics, although some mollic or umbric horizons can be found in few places. These soils are mainly associated with basic rocks and isothermic climates. They belong to many groups such as Ferralsols, Nitisols, Acrisols, Cambisols and Vertisols and especially Lixisols, and the presence of dark topsoil is reflected by the modifiers Mollic, Umbric, or Hyperhumic. In general, these soils are more productive than other tropical soils.

The area covered with tropical black soils is not very extensive. Most of them are associated with the humid savannas and semi-deciduous forests. Their use in agriculture depends on the density of population and the level of agricultural development in the country. Carbon storage is limited in such soils, and organic matter may be easily mineralized when the soils are ploughed. These soils are vulnerable to many degradation processes such as water erosion, compaction, nutrient depletion etc.

12 | Brazilian tropic



Profiles of tropic black soil. Location: Municipality of Corumbá, Mato Grosso do Sul state, Brazil

The dominant group of black soils in Brazil is the tropical black soils, with parent materials derived from basalt, gabbro and diabase (Demattê, Vidal-Torrado and Sparovek, 1992) or calcareous rocks (Maranhão *et al.*, 2020). The dominant climate is tropical (dry, with moderate water deficiency or semi-arid). Soil profiles, in general, occur on flat to strongly undulated slopes, uplands and backslopes, with surface horizons up to 65 cm thick and soil profile depths less than 130 cm. They show high content of Ca and Mg, with a predominant loamy to very clayey texture. When in the lowest part of the slopes, due to the presence of expansive clays (smectites), soils are very hard when dry and very sticky when wet. In some areas with gentle slopes, soils are poorly drained (Pereira *et al.*, 2013). The tropical black soils represent a hotspot, and they occur in small extensions under specific soil-forming conditions. The vegetation in many sites is designated as “dry forest” that includes tropical deciduous forest, with high canopy trees and rich plant undergrowth (Caatinga, tall deciduous and semi-deciduous forests in dry semi-arid climates; and the Cerrado, a mixture of open grasslands, shrub lands, open woodland, and closed canopy woodlands).

2.4.6 Black soils in highlands

In highlands, black soils may be found under several ecosystems at different elevations. Black soils are widespread under alpine meadows in temperate areas and under páramos in tropical mountains. These highland grasslands produce a high amount of root residues, which are responsible for dark humus accumulation. Depending on the precipitation, these soils may be rich in exchangeable bases or

strongly leached. In the first case they are classified as Phaeozems, and in the latter case as Umbrisols.

Since multiple mountain ecosystems other than alpine meadows have black soils, the exact area covered with mountainous black soils is not well recorded. Their use varies depending on the ecosystems. In páramos and in alpine meadows they are used mainly as pastures. Water erosion and compaction due to overgrazing are the most common degradation processes in these soils



13 | The Kyrgyz highlands



Tien-Shan Mountains

Kyrgyzstan is very mountainous and black soils develop in the mountains under grasslands. Their distribution is determined by the elevation of the terrain, and also related to the exposure, steepness, shape of slopes and other regional factors. The exposure of slopes has a great influence on the formation of mountain black earth soils. The slopes of the northern and northwestern expositions are more protected from significant insolation, so they create favourable conditions for the diversity and good growth of herbaceous vegetation, made up of bushes of rosehip, stem, barberry and woody vegetation. Under a lush variety of grass and cereal grass, black earth leached from carbonates are formed (Shpedt and Aksenova, 2021). Mountainous conditions determine the unique morphological shape and physico-chemical properties of black soils located on uplifted plains, characterized by a dark brown colour, high content of humus (up to 10 percent) that penetrates deeply down the profile. In the composition of humus, humic to fulvic acids ratio exceeds 1, with deep leaching from carbonates, a neutral reaction of the upper and weakly alkaline of the lower horizons, and high cation exchange capacity (30 to 40 Cmol/kg¹ of soil). These soils are characterized by relatively high gross content of nutrients (Shpedt and Aksenova, 2021). These soils differ from the mountain-valley ones by a more developed sod layer, sharp differentiation of the soil profile, a dark brown, almost black colour, higher humus content (up to 15 percent), and higher cation exchange capacity (Shpedt and Aksenova, 2021). Annex I, Section A.3.2 for more information.

2.4.7 Anthropogenic black soils

Anthropogenic (or human-made) black soils constitute a specific group where its dark colour depends both on organic matter and the presence of charcoal particles. Ever since humans became sedentary and practiced agriculture, they have been confronted with the need to manage their organic refuse. Refuse was initially just added to the soil where it may have somewhat increased soil organic matter levels. In most cases this addition resulted in only small increases in soil organic carbon, as a new equilibrium developed rapidly. Especially in tropical areas, where high temperatures and abundant moisture are conducive to rapid decomposition, effects were likely small. However, under certain conditions, the addition of organic refuse has modified soil properties, with soil becoming darker and eventually almost blackish and containing (substantially) higher amounts of carbon and nutrients. Under these conditions humans acted as soil-forming agents, resulting in anthropic black soils or Anthrosols (IUSS Working Group WRB, 2015).

Soil taxonomists recognize several types of Anthrosols, based on the diagnostic characters of the anthropic upper horizon. Important types are the Plaggic Anthrosols,

which originated by the use of bedding material for livestock, consisting of sods and excrements, on agricultural land (Pape, 1970; Giani, Makowsky and Mueller, 2014); Hortic (from the Latin hortus, meaning garden) Anthrosols, and Pretic (from the Portuguese preto, meaning black) Anthrosols. Pretic Anthrosols are usually dark-coloured, deep (the pretic horizon is at least 20 cm thick, but can be up to 100 to 200 cm due to intense bioturbation by ecosystem engineers such as earthworms), well-drained, sandy to clayey soils, with higher values for pH, organic C, total, extractable and available P, exchangeable divalent cations (Ca and Mg), CEC, and base saturation than the surrounding soils, while the amounts of extractable Fe is lower. The darker colour is both due to the inputs of charcoal and to biological processes (melanisation).

There are several specific threats to anthropic black soils. Intensive agricultural use can result in superficial erosion, nitrate losses, and the resulting lowering of pH and increased levels of extractable Al can also result in animal-species losses (Demetrio *et al.*, 2021). Intensive agricultural use and subsequent erosion is also a cultural loss. More information about Anthropogenic black soils in Annex I.



14 | Terra Preta do Índio



Terra preta do Índio soil and landscape, Brazil.

The most accepted hypothesis for genesis of these soils, based on pedological and archaeological evidence, is that they were formed unintentionally by pre-Columbian Amerindian societies in the Amazon basin (Kern and Kampf, 1989; Schmidt *et al.*, 2014; Kern *et al.*, 2019). The anthropic A (Au) horizons have a thickness up to 200 cm and colours ranging from very dark to black, with yellow or red colours in the subsurface horizons, marking a clear differentiation in the profile. By definition, the Anthropic horizon is marked by high fertility, when compared to adjacent soils, high contents of P, Ca and Mg, and stable organic matter (usually as charcoal), in addition to the presence of cultural artefacts. In general, they are well drained and have a texture ranging from sandy to very clayey, with a clear differentiation between anthropic A horizon (with loamy sandy, sandy loamy and clay textures) and subsurface horizons (with clay-sandy and clay textures) (Campos *et al.*, 2011). Estimates for the whole Amazon basin range from 0.1 to 0.3 percent (Sombroek *et al.*, 2003) to 3.2 percent (McMichael *et al.*, 2014) or even 10 percent (Erickson, 2008), with areal estimates ranging from 600 to 600 000 km². The rate at which such soils develop have not been quantified. However, because of feedback between human activity and soil amelioration, it is likely that incipient Terra Preta do Índio soils did develop within a few decades (Van Hofwegen *et al.*, 2009). Attempts are being undertaken to recreate such soils (Terra Preta Nova), however with incomplete knowledge on the recipe of Terra Preta do Índio formation, such attempts have not yielded large successes (Lehmann, 2009) and the literature on Terra Preta Nova in the last decade is very scant. In the Colombian Amazon region, these soils have been reported along the Caquetá river (Mora, 2003) and along some small tributaries of the Amazon river (Morcote-Ríos and Sicard, 2012). Most of the indigenous inhabitants of the Colombian Amazon basin have access to both natural soils and Terra Preta. For the Middle Caquetá river region, reports show that Indigenous Peoples recognize these soils as the most suitable soils for agriculture (Galán, 2003).

Black soils may form in many other environments, but commonly they occupy minor areas. Of special importance are black soils formed on limestone: these soils are called Rendzinas in many classifications. In WRB (IUSS Working Group WRB, 2015) such soils are called Rendzic Leptosols and Rendzic Phaeozems. In these soils derived from rocks with high content of calcium carbonate, the topsoil is black and thick. These soils form mostly under humid and semi humid climates from tropics to taiga area climatic belts. In places these soils occupy significant areas. Being shallow, these soils have evident limitations for their use in agriculture, though in places they are successfully used both as arable lands and pastures.

In places, black soils also form on lignite shales and other carbon-rich materials. In these cases, the colour of the topsoil horizon depends not only on the content of organic matter, but also on the dark colour of the parent material. Some of these soils are known for high fertility, but others have regular properties similar to those formed on other parent rocks. Of special interest are ornithogenic black soils, which form in bird rookeries in Arctic and Antarctic islands and coastal areas. The main source of organic matter in these places are bird excrements, and these soils are extremely rich in P, which plays an important role in their geochemistry.



2.5 Regional characteristics of black soils

2.5.1 Africa

Africa is an extremely large continent ($30.4 \times 10^6 \text{ km}^2$), equalling more than the countries of China, United States of America, India, Mexico, and the whole of Europe combined. Africa is generally subdivided into seven geographical regions, each defined by distinct geology and climate and thus unique landscapes and soils (Jones *et al.*, 2013). The Mediterranean has dry, hot ($>35^\circ\text{C}$) summers and cool (10°C) winters, and rainfall that occur mainly in the winter. The vegetation is mainly shrubs and agriculture can only be productive if additional water is available. Soils tend to be rich in calcium and magnesium, but low in organic matter. Deserts, encompassing the Sahara, the Namib and Kalahari, and northern Kenya and Somalia are very dry and very hot, and have great daily temperature variability. The vegetation cover is therefore poor or non-existent, soils are shallow and stony, and arable agriculture almost impossible. The Sahel and Savannah cover almost half of Africa. Savannah is a mixed grassland and woodland, occurring next to the forest region. Soils are well-drained, with thin organic matter rich topsoils, and can support limited cultivation. Its fertility degrades quickly. Tropical Forests have rather constant temperature and have either rainy or dry conditions. Forests are thus characterised by high vegetative production with organic matter-rich, nutrient poor, and acidic. Mountains encompass the Atlas Mountains of North Africa, the highlands in the Sahara and southern Africa, the eastern Africa rift valley, and the Ethiopia highlands. The climate is hot and dry and is defined by altitude. Soils are varied and closely related to the geology due to limited development. Rivers and wetlands include the floodplains of major rivers, swamps, and forested wetlands. Soils are characterized by fluvial stratification, good drainage or waterlogged, and are typically fertile with high organic matter content. Lastly, southern Africa is unique due to its very old and stable geology, as well as warm and dry climate resulting in thin and moderately fertile soils. Various soil maps, covering the African continent, have been produced. They include the Soil map of the World (FAO-UNESCO, 1981), the Harmonised World Soil Database (FAO, ISRIC and JRC, 2012), and the

Soil Atlas of Africa (Jones *et al.*, 2013). Hartemink, Krasilnikov and Bockheim, (2013) reviewed the global soil mapping attempts. For determination of the black soils defined in the Soil map of the World (FAO-UNESCO, 1981), all Rendzinas, Kastanozems, Chernozems, Phaeozems, and Greyzems were included in the search. This yielded 55 polygons (out of 1 635), varying in composition of the selected soils from 5 to 100 percent and covering an area of only 64 666 km^2 , or 0.21 percent of the African land surface.

In the Soil Atlas of Africa (Jones *et al.*, 2013), only 367 of 13 693 polygons are defined as Kastanozems, Phaeozems, or Umbrisols; totalling 203 923 km^2 or only 0.67 percent of the African land surface. There are no Chernozems or soils with the mollic horizon in the Soil Atlas of Africa. This 203 923 km^2 comprises of 121 435 km^2 Phaeozems (59.5 percent), 55 746 km^2 Umbrisols (27.3 percent), and 26 742 km^2 Kastanozems (13.1 percent). It should therefore not be surprising that the available research on black soils in Africa is similarly sparse.

Eswaran *et al.*, (1997) state that Mollisols (Chernozems, Phaeozems and Kastanozems) dominate more in areas with a xeric soil moisture regime, covering Morocco and coastal Algeria and Tunisia. In Sub-Saharan Africa, black soils are restricted to isothermic areas, with base-rich parent materials and commonly occur in association with Luvisols and Lixisols.

Kastanozems are very fertile soils and thus favoured by farmers, although these soils may be subject to nutrient imbalances as a result of the increased calcium levels in the soil (Jones *et al.*, 2013). The soils may be droughty and will thus require irrigation in the hot, dry summer seasons to be productive. Kastanozems might be susceptible to wind erosion in the dry season and to water erosion in the wet season, especially if situated on steeper slopes.

Phaeozems are very productive if sufficient rooting depth is available. These soils can also be droughty, because the water-holding capacity is provided by the surface layer only. Phaeozems are also susceptible to wind and water erosion, similar to Kastanozems.

Umbrisols are prone to acidity, since they occur primarily in humid areas, and are thus particularly suited for woodlands. These soils therefore require significant lime application to increase productivity. The wind and water erosion risk of Umbrisols is similar to that of Kastanozems and Phaeozems.

Eswaran *et al.*, (1997) conclude that Mollisols (Chernozems, Phaeozems and Kastanozems) and Vertisols that have high available water holding capacity, mainly associated with the higher 2:1 clay content of

these soils and that only these soils plus Luvisols can be considered as prime agricultural land.

The average organic matter content of 58 black topsoil soils in south Africa was 1.8 percent, varying from 0.5 percent to 4.3 percent (Van der Merwe, Laker and Buhmann, 2002b). The study stated further that the organic matter content was proportional to the kaolinite content and acidity.

Van der Merwe, Laker and Buhmann (2002a) studied the clay mineralogy of 58 black topsoil soils in south Africa and concluded that more than 50 percent of the soils were dominated by smectite, one third by kaolinite, and the rest had an association of mica, kaolinite, and smectite in approximately equal proportions.

Smith (1999) contends that wildlife anthrax in the Kruger National Park of south Africa was more associated with the high calcium and alkaline pH ecology, typically associated with Calcisols and Kastanozems.

In a study on the genesis of black topsoil soils in south Africa, Van der Merwe *et al.*, (2002b) concluded that these soils cover about 23 000 km² and are mainly associated with mafic igneous or sedimentary parent material, but that climate seems to be the dominant soil forming factor, with the soils limited to areas with contrasting seasons, mean annual precipitation of 550 to 800 mm, and an aridity index of 0.2 to 0.5. These soils do not develop in areas with mean annual precipitation <500 mm, probably due to the lack of organic matter addition and/or the lacking preservation thereof. Fey (2010) also gives an excellent overview of the genesis, properties and distribution of black topsoil soils in south Africa.

Black soils cover only about 0.67 percent of the African land surface, and as such do not feature extensively in research literature. These soils are, however, amongst the most productive on the African continent and are therefore in serious need of detailed research investigation.

2.5.2 Asia

Asia is a huge region, and all the varieties of black soils are present there. One of the three largest black earth zones in the world is in China, where they are concentrated in northeast plain (Krasilnikov *et al.*, 2018). Chernozems are also found in Mongolia. In this chapter, two country case studies are presented for China, with extensive areas of black soils under grassland vegetation, and for Japan, with abundant black soils formed in volcanic ash deposits.

China

In the early stage of land reclamation in the northeast region of China, farmers called the black and soft soil with a plough depth (15 to 18 cm) as “black soils”, including black soil, chernozem, meadow soil, white clay soil, and dark brown soil etc. (Liu *et al.*, 2012). Its administrative regions include Liaoning province, Jilin province, Heilongjiang province and the eastern fourth league of Inner Mongolia Autonomous region (Chifeng city, Tongliao city, Hulunbuir city and Hinggan league), with a land area of 1 244 million km² (Tong *et al.*, 2017). In the northern and eastern region of China, because the growing season is both hot and rainy time, the vegetation grows abundantly in summer and accumulates a large amount of organic matter (Ding, Han and Liang, 2012). Due to the long and cold winter, microbial activities are restricted, which is conducive to the accumulation of organic matter, and soil organic matter accumulation is greater than decomposition, forming a deep black soil layer (Sorokin *et al.*, 2021).

Black soils in northeast China are mainly distributed in the Liaohe plain, Songnen plain and Sanjiang plain (38°43′ north ~ 53°33′ north, 115°31′ east ~ 135°05′ east) (Qin *et al.*, 2021). It is one of the three major black soil belts in the world within a range of 1 600 km from east to west and 1 400 km from south to north. The natural black soils have been developed in the Tertiary, Quaternary Pleistocene or Holocene gravel and clay layers. The unique climate, hydrological conditions and vegetation types in the region have laid a foundation for the accumulation of humus in the soil, forming a deep and fertile black soil layer, and black soils has become one of the most fertile soils in the world (Li *et al.*, 2020).

The thickness of the black soil layer (layer A) of natural soils is closely related to regional climatic conditions. Due to the transformation of natural soils into cultivated soils after reclamation, the black humus in the A horizon was rapidly decomposed, the black colour gradually disappeared and changed to a grey leached layer (B horizon). The colour of the A horizon in some soil types gradually changed to the colour of the parent material (Zhang, An and Chi, 2019). The black soil area in northeast China is divided by 45° north, with a thin black soil layer in the south and a medium thick black soil layer in the north. Most of the black soil layer is more than 30 cm thick, and soil organic matter content is more than 35 g/kg. The black soil layer and its organic matter content of meadow soil are similar to those of medium thick black soils (Li *et al.*, 2020).

Before the nineteenth century, the black soil area was an ecosystem with outstanding ecological services and

functions, with less interference from human activities, and a large number of animals and soil organisms inhabited and multiplied here (Liu *et al.*, 2019). Those black soils were most important carbon sinks in the global terrestrial ecosystem (Li *et al.*, 2020). Since the twentieth century, with the rapid development of modern agriculture and the continuous increase of the world's population, black soils have been rapidly devoted to farmland, and most of the black soil area was then cultivated land (Wen *et al.*, 2021). The black soil area in northeast China has been converted in an important commodity grain production base of China, thus playing an important role in ensuring national food security (Li *et al.*, 2020).

However, due to the intensive utilization of black soil resources, the natural fertility of black soils have been on a downward trend year by year, mainly in the following aspects decreased: soil organic matter content, the plough layer becoming shallower and harder, and soil air-water-heat transference functions worsening as well as soil fertility. Continuous cropping leads to serious soil degradation such as erosion and acidification processes; the soil erosion of slope farmland is serious, and leads to the serious degradation of black soils (Zhang *et al.*, 2021).

In recent years, the Ministry of Agriculture, the Ministry of Science and Technology, the Ministry of Land and Resources and the four provinces of northeast China have actively implemented high standard farmland construction, soil and water conservation, soil testing and formulated fertilization, soil organic matter increases, conservation tillage and other projects, forming a series of measures suitable for different regions and black soil types, such as subsoiling for soil compaction alleviation and soil preparation, reduced tillage and no tillage, straw returning, and increasing the use of organic fertilizers (Li *et al.*, 2021). The comprehensive technical mode and operation mechanism of black soil protection and utilization are to control the loss of black soils and keep water and fertilizer (Han *et al.*, 2018).

Japan

Andosols account for about 30 percent of the agricultural land in Japan and are widely distributed on volcanic mountains, hills and Pleistocene such as plateaus near active volcanoes. The main parent materials of Andosols are volcanic ejecta such as volcanic ash, pumice, and scoria. Andosols are rich in active Al and Fe as soil formation products such as allophane, imogolite, Al-humus complex, ferrihydrite, etc. The morphological characteristics of the soil profile

of Andosols in Japan are as follows: (1) the formation of an organic-rich, black and dark-coloured humic horizon, (2) the formation of an organic-rich, brownish humic horizon, mainly under forest vegetation, (3) the formation of a cumulic humic horizon, and (4) the formation of a buried humic horizon (Takata *et al.*, 2021). Andosols are unique among soil types in terms of their physical and chemical properties (Shoji *et al.*, 1993). That is: (1) fluffy and light texture; (2) high water-holding capacity; (3) high reactivity with fluorine and high phosphate absorption; (4) high cation exchange capacity (CEC) and predominant variable charge (charge depends on pH), and (5) low retention of base cations and acids under humid climate. These unique properties are closely related to the presence of short-range order minerals or humus. Andosols are known as productive soils on a global scale. In contrast, in Japan they had traditionally been regarded as poor productive soils, because low phosphorus contents often limit crop production in Andosols (root crops and potatoes are the most common crops, and paddy fields are rarely used).

In Japan, phosphate adsorption coefficient (PAC) is among the soil properties routinely measured in soil survey. Soil PAC allows farmers to determine the adequate level of phosphorus fertilization. The main factors controlling PAC in Andosols are organo-Al complexes and the Al in allophane and imogolite present at aqueous-mineral interface (Nanzyo, Dahlgren and Shoji, 1993). It has been recommended that the amount of phosphate (molten phosphorus) fertilizer applied should be targeted at 3 percent of PAC, and that Ca and Mg supplementation should also be applied. Matsui *et al.*, (2021a) reported that PAC showed more significant positive correlation with SOC compared to clay and silt-clay contents for Japanese Andosols.

After soil chemical improvement by enrichment of phosphate and bases, the Andosols zone has become a popular production area for root crops and tubers, taking advantage of its large, flat area, favourable physical properties and easy cultivation.

Under well drained conditions, Andosols accumulate the highest amount of organic matter of any soil groups in the world (Shoji, 1984). Humus in Andosols forms complexes with Al, which increase its stability against decomposition by soil microbes. Andosols is distributed over only 0.84 percent of the Earth's terrestrial area, but their SOC accounts for about 1.8 percent of the global SOC. Andosols accumulate more than twice as much carbon as other soils, and it covers 30 percent of Japan's total land area. Andosols are an important soil resource from the viewpoint of both Japan's food security and

global environmental conservation. According to the national soil carbon monitoring project in Japanese agricultural land from 2015 to 2018, the average of Andosols carbon stocks (0 to 30 cm) is 122 tonnes C/ha in paddy field, 117 tonnes C/ha in upland crop field, 154 tonnes C/ha in pasture fields, and 137 tonnes C/ha in orchard field (Matsui *et al.*, 2021b). Andosols carbon stock are much higher than the other soil groups such as Fluvisols, Cambisols, and Acrisols in Japan. Simulated total SOC stock (1970 to 2006) in agricultural lands in Japan (sum of SOC stock among all land-use types) using the Roth-C model were found to increase its SOC stock in Andosols, whereas decreased SOC stocks in all other soil groups (Yagasaki and Shirato, 2014).

Soil water erosion has been reported as a soil degradation process in volcanic highlands. Subsurface horizons of Andosols generally have a very high phosphate fixation capacity, and if the ploughed layer is lost due to soil erosion, soil fertility will be significantly decreased. Soil water erosion not only reduces soil fertility, but also it may affect the watershed environment because of water pollution through the discharge of eroded sediment into rivers. Rivers flowing through the Andosols zone often turn black after rainfall (Matsumoto, 1992). In general, soil aggregation is not strongly developed in the ploughed layer of Andosols; abrupt changes in soil texture among soil horizons are often observed due to the deposition of different volcanic ashes. These characteristics make Andosols prone to soil water erosion. Fujino and Matsumoto (1992) reported that the thickness of the ploughed layer (adjusted by soil carbon content) was reduced by about 40 cm compared to the surface horizon (adjusted by soil carbon content) of the adjacent semi-natural grassland. Shiono *et al.*, (2004) conducted field measurements of soil erosion under bare and cabbage cultivation in Andosols distributed area in northern Kanto region. They showed that sediment yield from the cabbage plot was much less than that from the bare plot, and they also pointed that sediment yield in the cabbage plot was influenced by the coverage of crop and crop residues on the field (Shiono *et al.*, 2004). Heavy rainfall is common during the rainy season and typhoon season in Japan, and it is important to avoid bare land at those times to control soil water erosion.

Based on these principles, soil water erosion and sediment control should employ appropriate combinations of agronomic measures, soil management, field management and mechanical methods. However, farmers rarely adopt agronomic and field management methods because they receive few direct benefits from their efforts and costs for the control practices.

Mechanical methods are difficult to adopt because of the huge budgets they require. However, the Ministry of Agriculture, Forestry and Fisheries (MAFF) supports these countermeasures. A subsidy system for multi-functionality in agriculture offers a grant under certain conditions to local action groups practicing field management methods. This support is grounded in the following ideas that agriculture plays multiple roles, including conservation of national land, water resources, and natural water discharge during a runoff event (Shiono, 2015).

2.5.3 Europe and Eurasia

In Europe, the zone of black soils (Chernozems, Phaeozems and Kastanozems) partly covers Hungary, Bulgaria, Austria, southern Germany, the Czechia, Slovakia, Romania, and the Balkan Peninsula (Krasilnikov *et al.*, 2018). An extensive area with black soils is reported in Ukraine of 34.2 million hectares. In the Republic of Moldova, black soils cover 86.4 percent of the territory of this small republic equaling 2.92 million hectares. However, the largest area, totaling 326.8 million hectares are found in the Russian Federation, in the central Chernozem region, the Volga region, the Northern Caucasus, the southern Urals and western Siberia. Further to the east, black soils occur in the plains and foothills of the Altai, on the outskirts of the foothills of the eastern Sayan. Black soils are widespread in the northern part of the Republic of Kazakhstan and occupy 107.7 million hectares, or 9.5 percent of the territory of the republic (FAO, 2022a). For Europe and Eurasia, we present three case studies, which represent typical areas of black soil distribution in temperate plain grasslands (Ukraine) and in the mountains (Kyrgyzstan) and one country (Poland) with a minor area of black soils under transitional forest-steppe vegetation. The Ukrainian case study is the most detailed one, as in this country black soils cover a major part of the national territory and there are extensive studies on the productivity, ecosystem services, and degradational status of such soils.

Ukraine

Black soils distributed in the territory of Ukraine include a group of soils with certain differences in their genetic origin and history of development. All of them share a high content of organic matter, leading to the formation of saturated dark topsoil, from dark gray to black. In general, in the WRB system, they are classified as Chernozems, Kastanozems and Phaeozems.

The evolution of Chernozems and other black soils lasted almost the entire Holocene, so it is a polygenic soil. Plant-climatic conditions had a great influence on the genesis of black soils with both steppe and meadow vegetation with strong turf contributing to the accumulation of organic material.

The most favourable conditions for black soil formation are in the southern part of the forest-steppe zone, and in the north of the steppe, where Haplic Chernozems are widespread. To the south of these subzones, the moisture deficit increases and the amount of plant precipitation and the depth of the root system decrease. As a result, the depth of a humus-enriched topsoil and quantity of organic matter decreases. To the north, on the contrary, the amount of moisture and the leaching of exchange cations increase, and the concentration of organic carbon also decreases. From west to east, the continentality of the climate increases, thus increasing the amount of soil organic matter in chernozems and reducing the thickness of the humus horizon with relatively stable total humus reserves in the profile. Biological activity has a similar dynamic, and it is greatly influenced by the unfavourable water regime, which depends on trends in continental climate.

The particle size distribution of these soils is determined by the parent rocks: loess and loess-like loams occupy an area of about 75 percent of black soils in the country. The lithology of parent material varies depending on the geological and geomorphological factors (Polupan, 1988). In general, clay content increases from northwest to southeast. The soil profile depth of black soils, rich in organic matter, varies from 60 to 120 cm and more, especially on the watershed plateau and on north facing slopes. Black soils are characterized by a dark grey colour, which gradually lightens to the parent rock. In Phaeozems with slight vertical clay redistribution, topsoil has a lighter colour of eluviation. Black soils of Ukraine have variable physical and chemical, water-physical and agrochemical properties. The spatial distribution of the soils of Ukraine on the plain has a well-defined latitudinal zonation, but within these natural zones and subzones local climatic, geological, and topographical factors complicate the situation that also affects the distribution of black soils. Since they are found in all climatic zones, it is worth noting certain features inherent in these localizations.

Luvic Greyzemic Phaeozems in Polissya are confined to loess islands. In the forested steppe, black soils are represented mainly by Haplic Chernozems, which are found on low-lying plateaus and high loess terraces. In the past, these areas were represented by steppe meadows. The second largest area in Polissya is occupied by Phaeozems and Luvic Chernozems. The

soil cover of the northern steppe is represented mainly by Haplic Chernozems, which were formed under the herbaceous-fescue-feathergrass steppes. The diversity of soils is associated with an increase in aridity in the subzone from north to south, which led to a decrease in the thickness of the humus layer, carbon content in the topsoil, depth of accumulation of carbonates, gypsum, and water-soluble salts. The southern steppe is dominated by Calcic Chernozems (Tonguic), formed under fescue-feather steppes in arid climates. The main component of the soil cover of the dry steppe are Kastanozems. In the Carpathians and the Crimean Mountains, black soils occur sporadically, in the first tier of vertical zonation.

Unfortunately, soil resources management in Ukraine, is not sufficiently balanced and does not ensure the preservation of soil fertility (Baliuk and Kucher, 2019). The current state of Ukraine's soil resources is characterized by intensification of soil degradation processes, which is due to the contradiction between the national tasks of soil conservation and private interests in obtaining a quick profit from agricultural activities. Therefore, the problem of conservation of soil resources and overcoming soil degradation in Ukraine requires new methodological approaches and comprehensive solutions in the organizational, informational, technological and financial spheres (Balyuk, Medvedev and Miroshnychenko, 2018). The issue is especially relevant in the context of the impact of global and regional climate change on soil resources and agricultural production (Borodina *et al.*, 2016; Kazakova, 2016) and the need to adapt land use to such changes (Kucher, 2017).

The vast majority of black soils are intensively used in agricultural production. Thus, purely chernozemic soils like Luvic Chernozems (6.0 percent), Haplic Chernozem (21.3 percent) and Calcic Chernozem (39.5 percent), together make up 66.8 percent of the area of arable land (Miroshnychenko and Khodakivska, 2018). This area grows almost the entire range of crops, and especially high yields are obtained in cereals, sunflower, sugar beet, canola and more.

However, this high productivity also involves extremely high risks. According to Yatsuk (2015), the ploughed agricultural land is 78 percent with a total ploughed territory of 53.9 percent. Almost 74 percent of agricultural land is privately owned, and 24 percent is state property. Ignoring crop rotations has become a daily practice, which causes soil fertility declines. Growing monocultures, saturation of crop rotation with energy-intensive crops leads to soil nutrient depletion, water-physical functions and chemical properties deterioration, and other negative consequences.

This became especially widespread with the advent of agricultural formations with small land areas, which led to a reduction in crop production and the transition to non-specialized short-rotation to crop rotation. In addition, the current market situation forces farmers to grow primarily energy-intensive crops, such as

sunflower, that leads to neglect of crop rotations (Yatsuk, 2015).

The prevalence of black soils determines their high importance for the global environment. According to the data (FAO, 2015), ecosystem services can be characterized as follows (Table 2.5.1).

Table 2.5.1 Generalized ecosystem service rating of specific soil groups (WRB)

Types of soils	Ecosystem services, score points				
	Food, feed and fibre production	Water regulation	Biological diversity	Climate change mitigation and adaptation	Other benefits
Chernozems	5	4	4	4	Erosion control
Phaozems	4	3	4	4	Erosion control
Kastanozems	3	2	3	4	Erosion control

Source: FAO, 2015. *Healthy soils are the basis for healthy food production*. Rome, Italy, FAO. <https://www.fao.org/documents/card/en/c/645883cd-ba28-4b16-a7b8-34babbb3c505/>

Current management of soil resources consists of the following components: 1) management of soil fertility reaching the maximum possible soil and climatic potential; 2) preservation of ecosystem services and soil functionality as a component of the biosphere; and 3) use of soil opportunities for carbon sequestration and its minimum emission in agricultural use.

Excessive soil ploughing, monoculture, no addition of organic fertilizers, with an excess of plant protection products and the lack of real monitoring of soil quality are all point towards the need to improve the management of soil resources. These apply to all types of soils, but mostly to black soils, due to their priority in use.

Soil organic carbon in Ukraine has a clear latitudinal gradient (Plisko *et al.*, 2018; Vyatkin *et al.*, 2018). When analyzing the distribution of values of organic carbon reserves in the layer of 0–30 cm in the soils of Ukraine with a resolution of 1x1 km clearly visible carbon-rich black soils Forest-Steppe and Steppe. The lowest values of soil organic are typical for sandy Podzolic soils of the Ukrainian Polissya zone, which, although not directly related to black soils, are

important for evaluative judgments. Organic carbon reserves are markedly declining in the arid zones of the Dry Steppe in the south of the country, which is described in the literature (Polupan *et al.*, 2015).

The distribution of data according to Table 2.5.2 shows that the values of organic carbon reserves for the black soils of Ukraine are very different. The high concentration of SOC in Meadow steppe (dark chernozem-like soils) and Chernozems (podzolic, leached, typical, ordinary, southern, meadow) contrasts sharply with lower concentrations in Gray forest soils (dark-gray forest soils). Thus, in the first mentioned group of soils, the SOC concentration is 83 to 85 tonnes C/ha, which is almost twice as much as Dark-gray forest soils (Luvic Gleyic Phaozems) (45 tonnes/ha). The content of organic carbon in Chestnut soils is intermediate and is 59 tonnes C/ha. The progression is as follows: Luvic Gleyic Phaozems (Dark-gray forest soils), Kastanozems (Chestnut soils), Chernozems (podzolic, leached, typical, ordinary, southern, meadow chernozems), Gleyic Phaozems (Meadow dark chernozem-like soils).

Table 2.5.2 Reserves of organic carbon in the layer of 0–30 cm in the main types of soils of Ukraine(according to Plisko *et al.*, 2018; Viatkin *et al.*, 2018)**Source:** Polupan, N.I. 1988. *Soils of Ukraine and increase of their fertility: Vol. 1. Ecology, regimes and processes, classification and genetic and production aspects* (In Russian). Kiev, Urogaiz.

Types of soils	FAO/WRB	Average SOC stocks, tonnes C/ha
Grey forest soils (Dark-grey forest soils)	Luvic Greyic Phaeozems	45
Chernozems (podzolic, leached, typical, ordinary, southern, meadow chernozems)	Chernozems (Greyi-Luvic Phaeozems, Luvic Chernozems, Chernic Chernozems, Chernozems, Calcic Glossic Chernozems)	83
Chestnut soils	Kastanozems	59
Meadow steppe (Meadow dark chernozem-like soils)	Gleyic Phaeozems	85

Note: Soil type specified according to the classification of soils Ukraine (Polupan, 1988)

Some of the main factors of soil degradation in Ukraine, along with the unbalanced land structure with significant overload of agricultural land, is erosion, loss of organic matter and loss of nutrients (Balyuk *et al.*, 2012; Balyuk and Medvedev, 2015; Boroday, 2019; National report on the state of the environment in Ukraine in 2018, 2020).

Thanks to agrochemical certification, which is carried out in Ukraine, the following degradation processes are well detected: loss of organic carbon, denitrification, loss of phosphorus, potassium, sulfur

and micronutrients, decalcification, contamination with heavy metals, contamination with persistent pesticides, radionuclide contamination, acidification, salinization and alkalization (Balyuk *et al.*, 2012; Miroshnychenko and Khodakivska, 2018; Yatsuk, 2018; National report on the state of the environment in Ukraine in 2018, 2020). In general, the types, prevalence and degree of various degradations can be traced according to Table 2.5.3, and some of them, according to Medvedev (2012), are irreversible.

Table 2.5.3 Distribution of soil degradation types in Ukraine**Source:** Medvedev, V.V. 2012. *Soil monitoring of the Ukraine. The Concept. Results. Tasks.* (2nd rev. and adv. edition). Kharkiv: CE "City printing house.

Type of degradation	Extent, percentage of arable land according to the degree of expression			
	light	medium	strong	sum
Fertility declines and reduced humus content	12	30	1	43
Compaction	10	28	1	39
Sealing and crusting	12	25	1	38
Water erosion, surface wash	3	13	1	17
Soil acidification	5	9	0	14
Waterlogging	6	6	2	14
Soil pollution by radionuclides	5	6	0.1	11.1
Wind erosion: loss of topsoil	1	9	1	11
Soil contamination with pesticides and other organic contaminants	2	7	0.3	9.3
Soil contamination with heavy metals	0.5	7	0.5	8
Salinization / alkalinization	1	3	0.1	4.1

Type of degradation	Extent, percentage of arable land according to the degree of expression			
	light	medium	strong	sum
Water erosion: terrain deformation by gullying	0	1	2	3
Off-site effects of water erosion	1	1	1	3
Lowering of the soil surface	0.05	0.15	0.15	0.35
Wind erosion: terrain deformation	0.04	0.23	0.08	0.35
Desertification	0.04	0.18	0	0.21

The degradation of black soils in Ukraine is mainly the result of the use of inappropriate agricultural technology (Balyuk *et al.*, 2010). Application of NPK fertilizers from the average value of 150 kg/ha in 1990 fell to 18 kg/ha in 2000. Recently, some positive dynamics have been observed, and in 2015 the average NPK application reached 50 kg/ha (Miroshnychenko and Khodakivska, 2018). However, these values still cannot provide a positive balance of nutrients.

Due to the degradation of black soils and desertification, biodiversity have been lost, small (and sometimes large) water bodies are drying up, eutrophication of water bodies, groundwater pollution is increasing, the concentration of greenhouse gases in the atmosphere is increasing, and so on. Virtually all soil properties deteriorate as a result of irrational economic activity, especially in the context of global warming and under the influence of agrochemical pollution. As a result, most of the territory of black soils is unsuitable or suitable to a limited extent for growing environmentally friendly agricultural products (Boroday, 2019), which is of direct importance to society.

To minimize anthropogenic pressure on soils, the concept of organization and functioning of soil monitoring was developed (Medvedev, 2012) as well as a version with an emphasis on the experience of leading European countries (Balyuk and Medvedev, 2015). Accordingly, a set of measures was proposed to mitigate the current state and achieve a neutral level of degradation not only of black soils, but also of all soils of Ukraine (Baliuk, Miroshnychenko and Medvedev, 2018). Monitoring the neutral level of degradation, will provide effective approaches to assessing the actual condition of soils according to developed indicators and standards, as well as designing a roadmap for cooperation in the agricultural, climate, ecology, the soil science and other sectors (Dmytruk, 2021).

Kyrgyzstan

Kyrgyzstan is one of the most mountainous countries in the world. Black soils are developed in the mountains under grasslands, and their distribution is determined by the elevation of the terrain, and also related to the exposure, steepness, shape of slopes and other regional factors. Mountain black soils are widespread in the northern Tien Shan, on the mountain slopes of the Tassa-Kemin and Kastek ridges, on the northern slope of the Kungei Ala-Too and relatively less on the northern slopes of the Kyrgyz and Talas ridges. Black soils also occupy a considerable area on the slopes of the ridges that border the intermountain depressions and hollows of the central Tien Shan, in the eastern part of the Kungei and Terskei Ala-Too, Dzhungal, Suusamy, Naryn and At-Bashin ridges, on the northeastern slope of the Fergana range. Chernozem soils are also found in the western Tien Shan, on the slopes of the Fergana, Chatkal and Alai ridges and on the mountain slopes of the ridges surrounding the Ketmen-Tiubinskaya depression. Mountain Chernozem soils occupy various height marks, beginning from 1 400 to 2 700 m on shady, wet slopes and terraced ledges. In the Karkyra tract at an altitude of 2 000 – 2 200 m above sea level, there is up to 1 000 mm of precipitation per year. The exposure of slopes has a great influence on the formation of mountain black soils. The slopes of the northern and northwestern expositions are more protected from significant insolation, so they create favourable conditions for the diversity and good growth of herbaceous vegetation, which is replaced by bushes of rosehip, stem, barberry and woody vegetation. Under a lush variety of grass and cereal grass, black soils leached from carbonates are formed (Shpedt and Aksenova, 2021).

Mountainous relief of Kyrgyzstan creates certain conditions for the formation of black soils: mountainous and mountainous-valley soils. Mountainous conditions of soil formation determined the unique morphological shape and physical and chemical properties of these

soils. Black soils located on uplifted plains and in the valleys are characterized by a relatively weak differentiation of the soil profile, a dark brown colour, and a relatively high content of humus (up to 10 percent) that penetrates deeply down the profile. In the composition of humus, the ratio of humic to fulvic acids ratio exceeds 1, it has a relatively narrow ratio of C: N = 8 to 9, deep leaching from carbonates, neutral reaction of the upper and weakly alkaline – of the lower horizons, and high cation exchange capacity (30 to 40 cmol/kg of soil). These soils are characterized by relatively high gross content of nutrients (Shpedt and Aksenova, 2021).

Mountain black soils differ from the mountain-valley ones by a more developed sod layer, sharp differentiation of the soil profile, dark brown, almost black colour, higher humus content (up to 15 percent), wider C: N ratio (9 to 11), and higher cation exchange capacity (Shpedt and Aksenova, 2021).

Root biomass of herbaceous vegetation is of great importance for forming the properties of black soils. According to Mamytov and Bobrov (1977) the number of roots accumulated in the 0 to 50 cm layer for the subgroup of Chernozems of the north Tien Shan mountains is on average 45.55 tonnes /ha, while for the Issyk-Kul Mountain Chernozems on the southern slope of the Kungei Ala-Too, the average is 44.61 tonnes /ha. In the northern Tien Shan mountainous tableland, Chernozems accumulate less root biomass than mountain Chernozems, within 29.60 tonnes/ha. In the Issyk-Kul basin, mountain and longitudinal Chernozems accumulate 34.26 tonnes/ha, while mountain chernozems accumulate 46.35 tonnes/ha. Thus, the annual inflow of root mass in the chernozems of mountain slopes is higher than in the mountain-hillsides.

As many authors note, annual root production represents one third of the total stock of organic matter in soil (Voronov and Mamytova, 1987). Thus, about 15.0 tonnes /ha of organic matter are accumulated annually in black soils of mountain slopes, and in the mountain-horizon soils this indicator is 9.90 to 11.4 tonnes /ha, which indicates the unevenness of biomass intake during their formation.

In the black soils in central Asia there is a correlation between C:N ratio and climatic conditions. The widest C:N ratio is observed in the Chernozems of the Issyk-Kul subgroup, as well as in the most humidified northern Tien Shan, and the lowest (in the western and inner Tien Shan). However, it should be noted that the first two subgroups are characterized by a wide C:N

ratio only in the upper sod layers, and from a depth of 15 to 20 cm it sharply narrows, for the latter, there is a narrow C:N ratio throughout the profile. In these soils this ratio is gradually narrowed from high humus to low humus soils, from 11.0 in low humus soils to 13.4 in black soils rich in organic matter. A wide C:N ratio in mountain slope soils is conditioned by the presence of a large amount of resistant residue in these soils.

All black soils of central Asia have a pH between 6.9 and 7.3 in upper humus horizons and 8.5 to 8.6 in lower carbonate ones. Mountainous black soils do not contain easily soluble salts. The cation exchange capacity of alpine black soils exceeds 50 cmol/kg. Calcium prevails in the sum of absorbed bases. Magnesium content slightly increases and only in some cases reaches 30 to 31 percent of the sum.

Black soils in Kyrgyzstan are characterized by quite good structural condition and high water retention capacity. Over 80% of the topsoil has an aggregate size of less than 10 mm and more than 0.25 mm. Sufficient moistening, dense grass vegetation, and activity of earthworms in these soils are the main structural forming factors. However, if proper agricultural techniques are not followed, mountainous black soils can quickly lose their structure. During ploughing and irrigation, a compacted layer is formed, which should be periodically destroyed by changing the ploughing depth.

Agricultural use of black soils in Kyrgyzstan depends on terrain and climate conditions. Tableland and valley black soils have high fertility and are used for sowing grain, fodder and potatoes under irrigation and rain-fed conditions. Horticulture and beekeeping are widely developed on these soils. Mountain black soils are used as spring and autumn pastures and as hayfields, in some places under rainfed agriculture for grain crops. If proper agricultural techniques are not followed, the mountainous longitudinal chernozem soils quickly lose their structure and easily succumb to erosion processes, especially in irrigated areas (Duulatov *et al.*, 2021).

In the zone of irrigated black soils, scientifically grounded crop rotations are of great importance. On rich Chernozem soils it is possible to introduce crop rotations without perennial grasses but with obligatory steam for winter crops, annual legumes and cereals for grain and hay (Mamytov and Mamytova, 1988). It is recommended to practice activities that contribute to snow retention (such as ridges, wing plants, etc.), to fight weeds (such as oats, mussels, etc.) and apply organic and mineral fertilizers. Mountainous chernozem soils are used as autumn to spring pasture lands and are under great pressure. Herbs from year to year,

productivity decreases, and the land is overgrown with prickly bushes and inedible weed vegetation. Farmers are insufficiently informed about special soil-protecting crop rotations, agrotechnical methods of zero tillage, there is practically no contour treatment, so they sow across slopes on lands with significant escarpment.

Improvement of pastures is possible only on relatively large and levelled areas – is the ploughing and sowing of legumes and cereals grass mixture. Good results are given by superficial improvement by harrowing, discarding with sowing of legumes and cereals grasses. The livestock load should be property distributed on rangelands, providing individual slopes or areas of rest, which will contribute to individual slopes or areas of rest, contributing to a good growth of natural herbs. Studies of many research institutes (Yusufbekov, 1968; Mamytov, 1973) show that a one-year rest of cereals and grass meadow-steppe pastures increases yield by 40 to 50 percent.

Ecosystem services of mountain regions preserve the aesthetic and recreational potential of nature, secondly, the production of oxygen and carbon dioxide assimilation, supply of products and materials. Mountain forests and meadows have the highest potential to create a favorable climate for life in the field of humidification. Sequestration (content) of organic C in mountainous longitudinal dark chestnut soils is 2.33 to 2.91 percent (humus 4.0 to 5.0 percent), in mountainous longitudinal low humus chernozems is 2.33 to 3.49 percent (humus 4.0 to 6.0 percent), and in mountainous longitudinal medium humus chernozems is 3.49 to 5.81 percent (humus 6.0 to 10.0 percent). In mountain black soils, the content of organic C ranges from 2.33 to 11.62 percent. Gross organic C stocks in the upper 0 to 25 cm layer of black soils are 50.54 to 92.47 tonnes /ha.

Poland

1st category of the black soils: Arable use for over 100 years. Black soils in the Silesian Lowland (SW Poland) have the highest agricultural productivity in Poland. They were described by Bieganowski *et al.*, (2013).

The black soils genesis is connected with climate fluctuation during the whole Holocene period as well as human impact, differentiating their morphology and properties depending on their position in the landscape. Soils in higher positions are well drained, but those situated in lower positions can be excessively moist in early spring. Draining of these soils guaranties proper soil moisture and water supply for plants during the vegetation season. Soil profile with SiL texture fulfill the criteria to Chernozems (IUSS Working Group WRB, 2015) with the sequence of soil horizons: Ap (0 to 26 cm); A (26 to 47 cm); ACg (47 to 60 cm); Cg (60 to 85 cm); Ckg (+85 cm). Very dark gray colour (2.5Y 3/1) humus horizons reached 47 cm. The soil indicates granular fine structure in the humus horizon and visible stagnic properties starting from ACg horizon. Earthworm channels and crotovinas are visible in the whole profile. The content of Total Organic Carbon (TOC) in the Ap horizon reach 2.13 percent and the stock of TOC achieving 120 tonnes/ha. Despite the carbonate absence in the surface horizon, soil pH is alkaline in whole profile and base saturation is in range of 90 to 100 percent (Table 2.7).

2nd category black soils: Meadow use for over 100 years. The profile is located on the Holocene floodplain (1.5–3 m above the river level) with varying degrees of drainage. The soil, despite the SL texture reached 33 cm thick humus horizon. The sequence of soil horizons as follows: Ap (0 to 33 cm); Cg1 (33 to 50 cm); Cg2 (+50 cm) and the redoxymorphic features appeared directly below the humus horizon. The morphology of the soil profile can presume that the humus horizon was created by the conditions of agricultural use. The evidence of deep ploughing is visible as an abrupt humus horizon boundary and as a granular fine structure of the humus horizon. Due to high humidity, the soil has a reduced biological activity. The content of TOC in Ap horizon reaches 3.18 percent and the stock of TOC achieve 142 tonnes /ha. Due to the carbonate absence, soil pH is acid in the whole soil profile with base saturation is in range of 25 to 41 percent (Bieganowski *et al.*, 2013) (Table 2.5.4).

Table 2.5.4 Selected properties of different types of black soils

Source: Bieganowski, A., Witkowska-Walczak, B., Głinski, J., Sokolowska, Z., Sławinski, C., Brzezinska, M. & Włodarczyk, T. 2013. *Database of Polish arable mineral soils: a review*. International Agrophysics, 27(3).

Properties	Explanation (short, referenced)	
	1st Category black soils	2nd Category black soils
Soil texture	silt loam (SiL)	sandy loam (SL)
Soil structure	granular, fine	granular, fine
Soil porosity	47 percent	40 percent
Soil colour	2.5Y 3/1	10YR 2/1
Soil chemistry	2.13 percent TOC, 0.18 percent TN, pHH2O 7.23, ECEC 30.0, BS 97 percent	3.18 percent TOC, 0.18 percent TN, pHH2O 4.8, ECEC 11, BS 25 percent

In Polish conditions, the majority of soils meeting the criteria of black soils are developed on carbonate-bearing thick loess deposits, alluvial and colluvial (humus-rich) materials, limestones and other carbonatic rocks. Black soils developed from loess poses islands in the loess belt in southern part of Poland. Black soils may also occur in flat positions in the river valleys and other depressions or footslopes. Some of them are present in the fine slopes and in the hilly areas where limestones have occurred.

Due to their high productivity potential, some of black soils were being intensively used as arable land already in the Neolithic period which is confirmed by archeological findings. Some areas covered by “wet” black soils were drained, which enabled their agricultural use as arable land but part of them remained unchanged, as grassland.

The black soils in Poland are primarily used for food and fibre production due to their high fertility. They were characterized in terms of their susceptibility to compaction and aeration constraints by Domzal, Głinski and Lipiec, (1991), as well as other authors. Most black soils are located far from contamination sources, therefore they are referred to as non-contaminated. This assumption was partly confirmed by a country-wide monitoring programme. Black soils under grasslands and forests are used for walking and contemplation. They may also provide cultural experiences due to archeological findings.

Black soils are important for climate change mitigation and adaptation. This part of ecosystem services is not widely implemented by agriculture because black soils are intensively used for food production. They undergo the degradation processes accelerated by a lowering pH and reduction in organic carbon content. The degradation processes of black soils in Poland are

indicated by soil acidification and the water erosion, which influence the loss of organic matter. The erosion process is usually accelerated by the tillage preferred by farmers. Due to their texture, black soils with higher content of clay are threatened by soil compaction.

2.5.4 Latin America and the Caribbean

Argentina

Black soils of midlatitude grasslands. In Argentina, most of the black soils are found as zonal soils in the grasslands of the eastern part of Pampa region, in the center-east of the country, within the limits of the temperate zone, roughly between the latitudes 31° south and 39° south (Figure 2.5-A). The Pampa is an extensive plain, in which totally flat areas alternate with gently undulating plains and with rolling landscapes, and several sub-regions are identified based on environmental features (Figure 2.5-B) (Durán *et al.*, 2011). In the eastern part of the Pampa, the mean annual temperature varies from 16 °C in the south to 19 °C in the north, and the mean annual rainfall varies from 750 mm in the southwest to 1 100 mm in the northeast. Spring and autumn receive the most rainfall, while winter has the least. According to Soil Taxonomy, the soil moisture regime is udic while flat and low-lying lands have an aquic moisture regime. The natural vegetation includes large grasslands and steppes with medium height perennial and annual grasses. (such as *Andropogon*, *Bothriochloa*, *Stipa*, *Poa*, *Panicum*, *Paspalum*). The landscape has been greatly modified by agriculture and livestock activities, and the original vegetation only remains in some areas of lower agricultural aptitude.

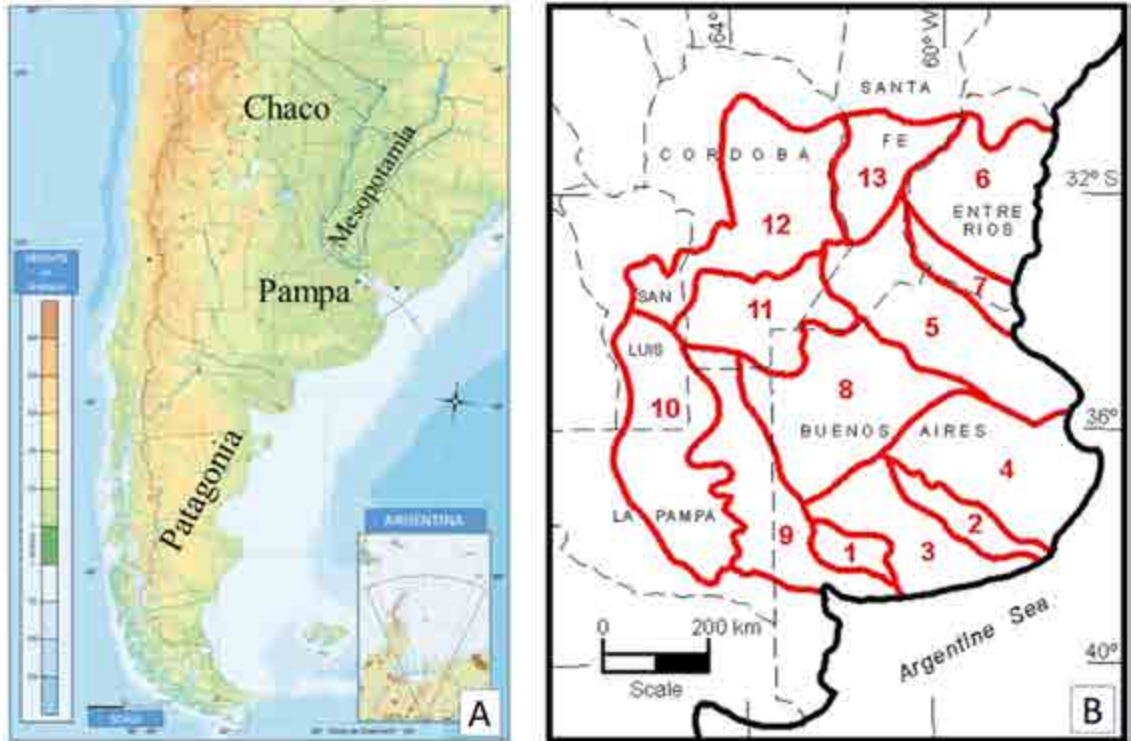


Figure 2.5 Distribution of main ecological regions in Argentina

A, Map of Argentina with the main ecological regions mentioned in this text. B, Sub-regions of the Pampa: 1- Hill range and piedmont of Ventania; 2- Hill range and piedmont of Tandilia; 3- Interrange Pampa; 4- Depressed or Flooding Pampa; 5- Undulating Pampa; 6- Mesopotamian Pampa; 7- Delta of the Parana river; 8- Sandy Pampa; 9- Polygenetic Pampean plains; 10- western or Dry Pampa; 11- Endorreic Pampa; 12- Piedmont Pampa (piedmont of the Córdoba and San Luis hill ranges); 13- Flat Pampa of Santa Fe
Source: Durán, A, Morrás, H., Studdert, G. & Liu, X. 2011. *Distribution, properties, land use and management of Mollisols in South America*. Chinese Geographical Science, 21 (5): 511-530.

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

The Pampa region is a large and deep sedimentary basin. Rocky hills occur only in the south of Buenos Aires province (Tandilia and Ventania hills) (Figure 2.5-B). The most recent Quaternary deposits lying on the surface, and therefore the parent material of Pampean soils, are loess and loessoid sediments to the east and aeolian sands to the west. The bulk of these sediments of Late Pleistocene-Holocene age came from andesitic and basaltic rocks and tuffs deposits from the Andes piedmont and northern Patagonia, as well as direct falls of volcanic ash from different sources in the Andes cordillera, to which are added contributions from a diversity of igneous, metamorphic and sedimentary rocks from other sources located around the region. As a consequence of aeolian transport by the predominant southwestern winds, a granulometric sorting of sediments took place, this being in the origin of the differentiation between the coarser sediments to the west and the finer to the east. Unlike the typical loess of the northern hemisphere, where quartz predominates, in the Pampean loess the set of light minerals is

characterized by the abundance of volcanic glass, while pyroxenes and amphiboles are usually abundant in the heavy fraction (Zárate, 2003; Morrás, 2020). With regard to the clay fraction, illite is the dominant mineral in most of the region accompanied by traces of kaolinite, while interstratified illite-smectite and smectite increase and become predominant to the east, close to the Parana river and the Atlantic Ocean (Durán *et al.*, 2011). A petrocalcic layer, considered Plio-Pleistocene in age and covered by a thin mantle (less than 1.5 m thick) of Holocene loess, is widespread in the southern part of the Pampa region. In the northern Pampa the calcrete, usually discontinuous, occurs at higher depth and is covered by a thicker mantle of Pleistocene and Holocene loess.

Pampean black soils are mainly Mollisols, and among them, Argiudolls and Hapludolls are the most representative (Durán *et al.*, 2011; Rubio, Pereyra and Taboada, 2019). Two sectors are characterized by a larger proportion of black soils: the Undulating Pampa to the northeast, and the hill ranges and the interranga

area to the south. In the northern part of Undulating Pampa (5-Figure 2.5-B) the drainage network is well defined, and the relief is gently undulating (slopes of about 2 percent and up to 5 percent). Typic Argiudolls are the most extensive; the mollic epipedon has at present about 2 percent of organic carbon, the argillic horizon is deep with a clay content that ranges between 30 percent to the west and 50 percent to the east, and the solum easily reaches 120 cm depth; calcium carbonate nodules frequently occur in the BC and C horizons. Also Vertic Argiudolls are common in the margins of the Parana-de la Plata fluvial axis, due to the higher content of expanding clay minerals in the soil parent material (Morrás and Moretti, 2016). In the southern part of the Undulating Pampa Vertic Argiudolls are very extensive and Vertisols are frequent, with Aquic Argiudolls and Argialbolls occurring in concave micro depressions.

On the other hand, in the Tandilia and Ventania mountain systems, loessic sediments have covered the igneous and metamorphic rocks with different thicknesses, from a few centimetres to almost to 2 m. All the soils belong to the Mollisol order, and their properties depend on the thickness of the loess cover and the contact with the underlying material. In the hill range of Tandilia (2-Figure 2.5-B) and in the Interrange Pampa (3-Figure 2.5-B), with a thicker sedimentary cover, the main soils are Argiudolls and Petrocalcic Paleudolls, with some Hapludolls. These black soils from the southern Pampa have higher contents of organic matter than the black soils from other areas of the Pampa (around 3 to 4 percent SOC). In the piedmont of Ventania (1-Figure 2.5-B), the moisture regime is transitional to ustic and the sedimentary veneer overlying hard rocks is thinner; dominant soils are Petrocalcic Paleustolls and Haplustolls, with some Calcicustolls.

Other Pampa sub-regions have a lower proportion of black soils than the precedent. In the Sandy Pampa (8-Figure 2.5-B) the most extensive black soils are Hapludolls. They consist of a recent superficial loamy sedimentary layer of about 30 to 50 cm depth where an A-C or A-AC sequence overlies the buried argillic horizon of a paleosol developed in a silty loam sediment. Depressed Pampa (4-Figure 2.5-B) has udic to acic regime, and soils are characterized by an excess of exchangeable sodium. Most black soils are represented by Natrudolls and Petrocalcic Paleudolls. The Flat Pampa of Santa Fe (13-Figure 2.5-B), north of the Undulating Pampa, is flat to gently undulating, with long slopes of less than 1 percent. The representative soils here are Typic Argiudolls, with a deep and highly clayey Bt horizon. In the western sector of the Mesopotamian

Pampa (6-Figure 2.5-B) close to the Parana river, Typic Argiudolls and Vertic Argiudolls are developed in a mantle of loess covering lacustrine smectitic sediments. Pampean black soils, originally high in organic matter and of very high natural chemical fertility, have been cropped without fertilization from the end of nineteenth century until recently (Viglizzo *et al.*, 2010; Durán *et al.*, 2011). The main crops are wheat, corn, soybeans, sorghum, barley and sunflower. Soybean is the only crop that has steadily increased its acreage in the last thirty years, while the area under the other crops remained relatively stable or has decreased slightly. Extensive livestock production is also another important activity in the humid Pampa. It was only in the early 1990s that acute depletion of nutrients, particularly phosphorus, became apparent and that the use of fertilizers began to spread in the region. This depletion is linked not only to the extraction of nutrients by crops but also to erosion.

Swelling black soils (Vertisols). In Argentina, Swelling black soils (Vertisols), are found in various regions, but they are particularly relevant in the southern part of the Mesopotamian region (which includes de Mesopotamian Pampa), and other sub-regions in the eastern part of the Pampean region. Vertisols can also be found in restricted areas of the Argentine Chaco and the Patagonian region, although they are not mentioned in this section due to their limited geographical distribution. Instead, the works of Moretti *et al.*, (2019) and Pereyra and Bouza (2019) can offer further information on these black soils.

The Mesopotamian region is an extensive area framed by the great Paraná and Uruguay rivers (Figure 2.5-A). The landscape is characterized by numerous streams dissecting the Plio-Pleistocene fluvial-lacustrine sediments, resulting in a gently undulating relief. The climate is humid subtropical, with annual rainfall ranging from about 1 100 mm in the south to about 1 400 mm in the northern part of the area. The hydric regime is udic, or eventually aquic. The vegetation is a mix of open savannas, wooded grasslands and semidry forests. In this geographical context Vertisols are the main soils, occupying about 3 million hectares.

The parent material of Vertisols of this region, as well as of associated vertic Alfisols and Mollisols, is made up of sediments of silty-clay or clay-loam textures, with a predominance of smectites in its clay fraction and quartz in the coarse one, and with a considerable proportion of calcium carbonate, some gypsum and manganese and iron oxides segregations. Unlike most of the Vertisols in the world, a large part of the Vertisols in the Mesopotamian region present horizons that are

described as argillic Bt, taking into account the notable increase in the amount of clay and the existence of clay coatings in the B and especially in the lower BC or C horizons (Cumba, Imbellone and Ligier, 2005; Bedendo, 2019). Many of these Vertisols have a linear “gilgai” micro-relief. Almost all Vertisols correspond to the Hapluderts taxonomic great group. In most Swelling black soils the A horizon has a silty-clay loam texture and a high content of SOC (2 to 3.5 percent). In turn, the B horizon is silty-clayey to clayey, very dark up to 70 cm depth (10YR2/1 – 10YR3/1, moist), very dense and with poor drainage. The transitional BC horizon has always some fine CaCO₃ in the groundmass and abundant calcareous nodules (gley features and small gypsum crystals can be occasionally found). The CEC in the epipedon is around 35 cmol/kg and in the Bt is around 45 cmol/kg, and they are highly saturated. These soils are mainly devoted to mixed crop-livestock production, a small proportion are used to grow rice. In recent years, soybean growing, has taken over these soils. Because of their low permeability, undulating relief, and summer rainstorms, these soils are prone to erosion. No-till and contour-line cultivation are now widely used to mitigate erosion problems.

In the rest of the Pampean region, Vertisols occur in the east of the province of Buenos Aires, in two clearly differentiated sectors: that of the Undulating Pampa and the coast of the Río de la Plata and in the littoral area of the Depressed Pampa (Figure 2.5-B).

Swelling black soils are present in moderate proportion in the southeastern part of the Undulating Pampa (5-Figure 2.5-B), developed in loessic Upper Pleistocene sediments with a silty-clay loam texture and about 50 percent smectite in the clay fraction. The Hapluderts in this region, similarly to those in the Mesopotamian region, also present illuvial Btss horizons; the clay content is about 35 percent in the surface horizon, reaching between 55 to 60 percent in the Btss. In this region, the diapiric structures and the “gilgai” micro-relief are poorly expressed. The O.C. content is around 2 to 2.5 percent in the A horizon. The CEC oscillates around 24 cmol/kg in the A horizon and 37 cmol/kg in the B horizons. Unlike Mesopotamian soils, these Vertisols have lower CaCO₃ content in the Bt and do not present gypsum at the base of the profiles. Towards the north of the Undulating Pampa, along a strip of about 60 km wide that borders the Paraná-de la Plata fluvial axis, some Vertisols appear on relief tops and slope heads, associated to Vertic Argiudolls (Morrás and Moretti, 2016). These vertic soils are developed in sediments with a moderate to high proportion of smectite; they have diapiric structures, although no

“gilgai” micro-relief is observed in the field, maybe as a consequence of the intense agricultural and urban intervention in the area. Their A horizon is brownish black (7.5YR3/2), with a SOC content about 2 percent and a 30 percent clay. In turn, the Btss horizon has more than 50 percent clay and is darker than the topsoil (7.5YR2/2) though the SOC is about 0.7 percent at 45 cm depth. Due to their close association in the landscape with Vertic Argiudolls, these Vertisols are used both for agriculture and for urban development.

The coastal plain of the Río de la Plata constitutes a long strip of about 5 to 10 km wide and about 110 km long from the city of Buenos Aires to the south. These sediments correspond to a middle Holocene marine ingression. Most of the Vertisols are Natracuerts, although Hapluderts are also present (Imbellone and Mormeneo, 2011). The clay fraction ranges between 50 and 70 percent in the solum, decreasing towards the base of the soils. The colour of the surface horizons is dark (10YR2/2 in some cases, 2.5Y3/2 in others) and the SOC content is around 2 percent. In the A or Ag horizon the CEC and the base saturation are high, with the pH oscillating around 8 and increasing to pH 9 in the Bssg horizon.

On the other hand, Swelling black soils cover a large and extremely flat area in the easternmost sector of the Depressed Pampa, in a strip about 30 km wide from the coast (4-Figure 2.5-B). Vertisols are developed in muddy sediments deposited in the plain during Upper Pleistocene and Holocene marine transgressions. They are very clayey from the surface, with high levels of salinity and alkalinity. Swelling black soils here are Natracuerts and Hapluderts. The SOC content is very high, ranging between 2 and 15 percent. The clay content oscillates between 40 and 50 percent in the A horizon and amounts to 55 to 65 percent in the Btss horizon. Both the CEC and the base saturation are high, while the exchangeable sodium ranges between 15 and 25 percent in the Btss horizons. Due to the limitations imposed by the environment, these soils are used exclusively for livestock production.

Volcanic black soils. Andisols in Argentina are found in the Andean-Patagonian region (Figure 2.5-A) (Pereyra and Bouza, 2019). This is a belt of mountains extending from 37° south to 54° south in the southwestern part of the country. The average altitude is around 2 000 metres above sea level and the valleys are aligned N-S according to the Andean structure. Great lakes associated with moraine landforms are found along the region. The climate is cold humid and shows great spatial variability. Precipitation decreases markedly

from about 3 000 mm at higher altitudes to the west, to about 700 mm in the piedmont to the east. The vegetation is a cold-temperate humid forest called the Subantarctic phytogeographic province characterized by *Nothofagus*, also including *Araucaria araucana* among other tree species.

Surface sediments have great spatial variability, predominating colluvial deposits, tephra and volcanic ash, till, gravel and fluvial sands. Andisols are very frequent in glacial valleys, glaciofluvial plains, lower slopes, screes and morenic arcs. These soils can occupy any position in the landscape and can occur at any elevation. Their parent materials are volcanic ash or lapilli of mesosilicic to acidic composition, mixed in varying proportions with colluvial material and glacier materials. The soil temperature regime is cryic, and the soil moisture regime is udic, ustic, xeric or aquic. The most common profiles are O-A-Bw-C or O-A-AC-C. The surface mineral horizons are mollic, melanic or umbric; their colour is 10YR 2/1–2/2 (dry), the organic carbon is around 5 percent, the pH is around 5, the texture is sandy loam and the bulk density is below 1. They are characterized by a high content of allophanic materials and a strong phosphate retention. In general, these soils exhibit an incipient Bw horizon with a high CEC due to the presence of allophane and high organic matter content. According to the Soil Taxonomy the most frequent Andisols are Hapludands and Udivitrands. In the lower and humid areas of the landscape, usually on the floor of the glacial valleys, Andisols are hydromorphic and rich in organic matter (Endoaquands). The Andisols of Argentine Patagonia largely comprise protected natural areas and a small proportion are dedicated to afforestation with foreign species.

Black soils of subtropical regions. The Argentine Chaco is a large sedimentary plain in the center-north of the country that presents a variety of climatic and vegetation environments (Figure 2.5-A) (Moretti *et al.*, 2019). Rainfall is highest to the east, in the areas surrounding the Parana and Paraguay rivers (about 1 300 mm per year), gradually decreasing to 450 mm in the southwestern boundary of the region. Mean annual temperatures rise from 19°C in the limit with the Pampean region to 24°C in the northern border of Argentina. Unlike the Pampean grasslands, the vegetation in the Chaco is mainly characterized by forests and savannas, although herbaceous communities are typical in the extensive alluvial plains and wetlands of the eastern part. The geology of the Chaco is equivalent to the one described for the Pampa, although the surface

sediments differ somewhat in their composition, origin and distribution. Generally speaking, late Pleistocene loessoid sediments cover large areas in the central and western Chaco while Holocene fluvial silty and clayey sediments are widespread in the eastern alluvial floodplains. The scarce information available on the mineralogy of the Chaco soils shows compositional differences between different sectors of the region in relation to the existence of sedimentary contributions from different sources. Thus, the geochemical composition of the materials differs and consequently the fertility of the soils is varied. In the central and the western sectors, the soils are characterized by high phosphorus and potassium contents, related to the sediments contributed by Pampean Hills and Andes cordillera. Conversely, the eastern sector presents lower contents of those elements due to predominance of sediments from the Paraná basin.

Black soils are found in three distinct sub-regions: in the Mountain Chaco, in the Xerophytic Woody Chaco and in the Chaco's Grasslands and Savannas. The Mountain Chaco integrates the eco-region of Yungas, a subtropical forest which characterizes the mountain system of northwestern Argentina and within which the climate becomes more humid with the altitude. Black soils develop on gentle slopes, in the lower parts of the eastern piedmont. Argiudolls and Hapludolls are found in the most humid sectors, and Argiustolls and Haplustolls in sub-humid sectors. The texture of the parent material is varied but many are silt loam, the SOC content ranges from 1.5 to 2.5 percent, they are deep and are the most developed in the western Chaco. Rainfed agriculture is practiced on these soils, the main crops being beans, soybeans, corn and wheat. In the southernmost part of the Xerophytic Woody Chaco, in the limit with the Pampa, black soils appear in the eastern foothills of northern Pampean Hills. The soil parent material is constituted by loamy fluvio-aeolian deposits, and the dominant soils are Haplustolls. The pH of the epipedon is around 7, the SOC is about 1.8 percent and the content of soluble phosphorous is high (40 to 60 ppm P). These soils are used for extensive rainfed agriculture. Finally, the Chaco's grasslands and Savannas sub-region (also known as Sub-meridional lowlands) is an extremely flat and monotonous herbaceous plain that stretches north-south for roughly 300 kilometres and is bordered to the east and west by higher regions with forest vegetation. The edaphoclimatic regime is hyperthermic udic, and most soils exhibit hydromorphic and halomorphic features, with a wide variety of salty, saline-alkaline, and alkaline soils observed in connection to meso and

microrelief changes (Morrás, 2017). The majority of the territory is covered with Natracuolls with highly salinized Bt horizons (E.C. about 12 ds/m at 60 cm depth). The epipedon of most of these soils is composed of an A horizon that is only about 10 cm deep, dark (10YR 2/1, moist), with 20 percent clay and 2 to 4 percent organic carbon, and a Bt1 horizon that is dark (10YR 2/2, moist), with 30 to 40 percent clay and 1 percent organic carbon. Although the salty content in the subsurface horizons is substantial, the textural and structural difference between the A and Bt horizons acts as a barrier to the capillary rise of saline water, which is why the A horizon is non-saline (EC <4 ds/m). When this barrier is breached by conventional tillage, salt levels rise and salty efflorescence forms on the surface. Because of the significant danger of deterioration, the only use for these black soils is grazing.

Brazil

Genetic groups and geographical distribution.

Three groups of soils fit the definition of black soils in Brazil. The first and dominant group is the Tropical black soils, with parent materials derived from basalt, gabbro and diabase (Dematê, Vidal-Torrado and Sparovek, 1992) or calcareous rocks (Pereira *et al.*, 2013; Melo *et al.*, 2017; Maranhão *et al.*, 2020). The dominant climate is tropical dry, with moderate water deficiency or semi-arid. Soil profiles, in general, occur on flat to strongly undulated slopes, uplands and backslopes, with surface horizons up to 65 cm of thickness and soil profile depths less than 130 cm. They show high content of Ca and Mg, with a predominant loamy to very clayey texture. When in the lowest part of the slopes, due to the presence of expansive clays (smectites), soils are very hard when dry and very sticky when wet. In some areas with gentle slopes, soils are poorly drained (Dematê, Vidal-Torrado and Sparovek, 1992; Pereira *et al.*, 2013; Melo *et al.*, 2017; Maranhão *et al.*, 2020).

The second group, the Midlatitude black soils, represent a relict in the landscape, formed in much cooler and drier conditions in the mid-Holocene, according to Behling (2002). Today, the climate is warm and moist. The parent material is mainly basalt and diabase, and siltstone and argillite. The soils are generally shallow, with the surface horizon thickness reaching 60 cm and the soil profile depth is less than 100 cm. They have high content of Ca and Mg, and a loamy to very clay texture. When poorly drained and with expansive clays, the consistency is very hard when dry and very sticky when wet (Almeida, 2017).

The third group is the Anthropogenic black soils, represented by the Amazon Dark Earths (ADEs), also called locally “*Terra Preta de Índio*”. The most accepted hypothesis for the genesis of these soils, based on pedological and archaeological evidence, is that they were formed unintentionally by pre-Columbian Amerindian societies in the Amazon basin (Kern and Kampf, 1989; Schmidt *et al.*, 2014; Kern *et al.*, 2019). The anthropic A (Au) horizons have a thickness up to 200 cm and colours ranging from very dark to black, with yellow or red colours in the subsurface horizons, marking a clear differentiation in the profile. By definition, the Anthropogenic horizon is marked by high fertility, when compared to adjacent soils, high contents of P, Ca and Mg, and stable organic matter (usually as charcoal), in addition to the presence of cultural artefacts. In general, they are well drained and have a texture ranging from sandy to very clayey, with a clear differentiation between anthropic A horizon (with loamy sandy, sandy loamy and clay textures) and subsurface horizons (with clay-sandy and clay textures) (Campos *et al.*, 2011).

In Brazil, the Tropical black soils represent a hotspot and they occur in small extensions under specific soil forming conditions. The vegetation in many sites is designated as “dry forest” including: Tropical deciduous forest, with high canopy trees and rich plant undergrowth (Caatinga, tall deciduous and semi-deciduous forests in dry semi-arid climates) and the Cerrado (a mixture of open grasslands, shrub lands, open woodland, and closed canopy woodlands). In the Midlatitude black soils, there is a uniqueness of grasslands in a plain to slightly undulated landscape referred to as “campos” or “pradarias” (Overbeck *et al.*, 2007). The vegetation is dominated by grasslands, from plain to a slight shrubs and occasional small trees within the grass matrix (Cabrera and Willink, 1980). In other regions, trees form gallery forests and shrub forests (Overbeck *et al.*, 2006).

The Anthropogenic black soils (ADEs) occur in discontinuous patches, and they have varying sizes, from less than a hectare up to ten times this area, usually near to watercourses and floodplains, in adjoining higher elevations (*Terra Firme*). Their locations are associated with availability of food and other resources from different environments (land and rivers); and the topographic position allowing the control of access routes and visibility for defence (German, 2003).

Land use and management. Regarding land use of Tropical black soils in Brazil, the dry climate, high slopes and the shallow soils with presence of rocks limit intensive agriculture. However, in small farms

they represent an important asset, and are cultivated with annual crops, horticulture or used as native pastures. In the “*campos or pampas*” region, the native grassland of the Midlatitude black soils has been used for extensive livestock (beef and dairy cattle, and sheep) (Overbeck *et al.*, 2005), since the seventeenth century. Recently annual crops such as corn, rice and soybeans, and managed pasture with exotic species, are replacing the traditional systems (Pillar, Tornquist and Bayer, 2012; Roesch *et al.*, 2009; Almeida, 2017). Animal overgrazing on the native grass fields, can be considered a soil management threat (Overbeck *et al.*, 2007). Andrade *et al.*, (2015) showed that a large area of native grassland was lost, mostly due to the conversion to arable fields (mainly soybeans) or tree plantations. In some areas, they were nearly completely transformed into croplands, and a considerable part of the remaining grasslands, although mapped as conserved environments, have been degraded by the introduction of exotic forage species, deliberately seeded in some areas and colonized by different means of dispersion in others.

Across the Amazon region, Anthropogenic black soils are largely used with crops in small farms, where the management is based on the high natural fertility. In some sites, the surface soil is removed and sold as substrate for pot plants, which represents a threat for the farmers and loss of a cultural heritage.

Ecosystem services. The areas of Tropical black soils are recognized by their beautiful and diverse landscapes and the valuable underground water reserves. Some of the karst areas served as a shelter and source of food since the dawn of mankind in the Americas, as proven by cave paintings and archaeological remains. Besides the scientific, cultural, tourism, and environmental value, these areas are also important for small farmers, due to the high fertility of the soils, allowing for high production of many crops and forage for animals. In the Midlatitude black soils, the forage production for livestock was dominant. By the end of the twentieth and early twenty-first centuries, this usage changed to intensive crop cultivation in the summer, with corn, wheat, and, in smaller size farms, irrigated rice (Pillar, Tornquist and Bayer, 2012; Roesch *et al.*, 2009; Almeida, 2017). The areas of ADEs are widely used in food production, in the so-called subsistence agriculture with the cultivation of crops such as cassava, corn, beans, vegetables, cocoa, coffee, fruit trees and pastures, in small and medium farms (Santos *et al.*, 2013; Cunha *et al.*, 2017; Santos *et al.*, 2018a).

The natural coverage in protected areas of tropical and midlatitudes black soils favor infiltration and conservation of water, and the hydrological fluxes are restricted by presence of underground bedrocks or by the shallow soil profiles. The grassland ecosystems of “*campos*” ensures the conservation of surface water resources and groundwater and offers scenic services with a major tourism potential. ADEs are associated with watercourses, supporting, in many cases, riparian forests. They play an important role in maintaining and conserving water resources. Their higher water holding capacity and better soil physical properties ensure adequate flow and storage of water in the soil profile.

The black soils in Brazil occur in small areas but with different biomes, such as Amazon, Cerrado and Caatinga. Even in the least known “*campos*” environment of the south region, with the Midlatitude black soils, a high biodiversity is observed with about 2 200 plant species, and at least nine grassland species are endemic (Overbeck *et al.*, 2007). In ADE areas, Lins *et al.*, (2015) found traces of exotic and native species, evidence of pre-Colombian human occupation. In addition to the accumulation of organic carbon, the Tropical black soils of semi-arid regions have high stocks of inorganic carbon in the form of carbonates. Studies show the potential to mitigate greenhouse gas emissions in areas converted to agriculture by using systems with legume-based crop rotations combined with no-till (Pillar, Tornquist and Bayer, 2012). In the “*campos*” environment, Conceição *et al.*, (2007) observed an increase in the C stocks (0 to 40 cm) under the lowest grazing pressure management, where the values for high grazing pressure were of 103 tonnes C/ha and 140 tonnes C/ha for lower grazing. The ADE soils present, on average, up to six times more stable organic matter than adjacent soils without an anthropic horizon, appearing as a large reservoir of SOC. Studies show variations in the evolution of greenhouse gas emission in crop systems. Cunha *et al.*, (2018) found efflux values for forest environments of 1.91 $\mu\text{mol}/\text{m}^2/\text{s}$, for pigeon pea of 2.29 $\mu\text{mol}/\text{m}^2/\text{s}$ and for pasture of 2.26 $\mu\text{mol}/\text{m}^2/\text{s}$, showing that forested environments emit less carbon into the atmosphere than cultivated ones. Campos *et al.*, (2016), studying the CO_2 efflux in the same region, found, in ADE areas cultivated with cocoa, an efflux of 5.49 $\mu\text{mol}/\text{m}^2/\text{s}$, while when with coffee, CO_2 efflux was 3.99 $\mu\text{mol}/\text{m}^2/\text{s}$.

Carbon stock and stability. The C content for Tropical black soils varies from 4.9 to 111.7 g/kg (Dematê, Vidal-Torrado and Sparovek, 1992;

Pereira *et al.*, 2013; Melo *et al.*, 2017; Maranhão *et al.*, 2020). The Cseq potential of representative soil profiles shows values from 72.8 to 188.5 tonnes C/ha, for superficial horizons, and from 72.8 to 422.9 tonnes C/ha for the soil profile. The Midlatitude black soils have C content from 7.6 to 50.4 g/kg (Pinto and Kämpf, 1996; Almeida, 2017). The Cseq potential of representative soil profiles shows values from 59.9 to 269.5 tonnes C/ha, for superficial horizons, and from 112.7 to 278.1 tonnes C/ha, for the soil profile. About stability, the high aggregation in natural conditions is a positive factor on both groups of black soils, especially under grasslands, but it is significantly modified when intensively cultivated. The ADEs show C contents from 0.9 to 98.9 g/kg in the anthropic A horizons. In representative profiles of Brazil, the Cseq varied from 26.1 to 348.1 tonnes C/ha for superficial horizons (Cordeiro, 2020).

Major threats and degradation processes. In Tropical black soil salinization, in semi-arid climates, and nutrient leaching are major threats. Another threat is soil erosion, mainly due to location in higher slopes and the incidence of high intensity rains, mostly concentrated in a short period of time. For Midlatitude black soils, overgrazing in the native pastures, erosion and the invasion of exotic species, grasses and shrubs or trees are the most important threats. When intensively cultivated for agriculture, soil compaction and sealing increase (Overbeck *et al.*, 2007; Roesch *et al.*, 2009; Andrade *et al.*, 2015; Modernel *et al.*, 2016). According to Silveira *et al.*, (2017), in the “campos” (Pampas biome), the usage with summer croplands increased 57 percent in 15 years, with a strong impact due to drainage (except for rice paddies), accelerating organic matter decomposition, thus reducing SOC. The ADEs have also undergone changes, with the natural forest substituted by agricultural systems (Aquino *et al.*, 2014). In the short term and in small farms, these changes have not severely affected the soil fertility (Oliveira *et al.*, 2015a; 2015b; Santos *et al.*, 2018b). However, it is expected that practices such as burning for area cleaning, animal overgrazing and the non-replacement of soil fertility, will certainly lead to acidification, erosion, compaction, and loss of soil biodiversity and cultural heritage.

In the Tropical and Midlatitude black soils, the presence of expansive clays (smectites) limits mechanization and influences the water permeability and infiltration. The increased pressure by livestock systems is leading to overgrazing, thereby reducing the potential of the native grassland fields. Crops systems are implemented

in these lands without proper evaluation of potential and limitations. In the last decades, the advance of the agricultural frontier over forested areas in the Amazon has been a major threat to the ADEs, especially in the region called “Deforestation Arc”, a Cerrado-Amazon Ecotone that extends from Maranhão to Rondônia States (Cohen *et al.*, 2007), which major expansion of planted forestry, agriculture, pastures and the extraction of non-timber products. The status of black soils degradation has still to be evaluated and much research is needed. Emphasis should go on losses of SOC and water erosion, when intensively mechanized and after changes in land cover, as well as loss of biodiversity due to competition with exotic species in the grasslands. Fewer studies are available for ADEs, and they are contradictory. Some indicate that agricultural usages (pastures, banana, forest, beans, cocoa and coffee) negatively influence physical attributes (density, porosity, macro and microporosity) in layers up to 20 cm deep. However, Cunha *et al.*, (2017) showed that ADEs cultivated with pigeon pea or with planted forest improved the soil physical quality, with increase in SOC, carbon stock and dominance of aggregates > 2 mm. The Midlatitude black soils played a central role in the cultural and economic history of Brazil. The residents of the South American Pampas (*Gaúchos*) developed a strong tradition based on the livestock in crop rotation with rice, soybeans, corn and wheat, which is still is reflected in their customs and daily practices. In the last decades, large farms have become dominant with major investments in crop production. The evaluation and zoning of areas suitable for grazing, crops, forest and preservation, can help to conserve the soils, and give ecological alternatives such as tourism (Roesch *et al.*, 2009). The ADEs are defined by cultural markers and their anthropological value. They are considered a National Heritage, according to the National Historical and Artistic Heritage Institute (IPHAN) and thus they should be protected. The highly fertile soils are essential for supporting Amazonian Indigenous Peoples and “caboclos”, with a rich diversity of foods being produced in small plots and family farms. Over the years, the expansion of agriculture and pastures for livestock in the Amazon changed landscapes and vegetation cover, promoting changes on ADEs and adjacent soils. Thus, one way of reducing degradation of the ADEs would be by intensifying the mapping of these areas, and to restrict their usage to family farmers and traditional communities, while promoting sustainable practices.

Chile

Peculiarities in genesis and properties. The vast majority of the soils of the southern Patagonia of Chile are of glacial origin, derived from the retreat of large masses of ice and subsequent entry of the sea through channels at the end of the Quaternary. This phenomenon modified the landscape creating undulating sectors that are locally called “vegas” or wetlands meadows. There is great variability in the type of soils associated with these wetlands where Histosol, Fluvisol, Gleysols, Regosols, Solonchak, Solonetz and Vertisols can be found (Filipova *et al.*, 2010). The vast majority of these soil types contain large amounts of SOC; but, they also differ in pH level (related to the absence/presence of carbonates) and the electrical conductivity. The mineral soils associated with wetlands have thick textures in the first horizons, however, as one goes deeper, finer textures are found, reaching semi-impermeable layers, giving them the ability to store and conduct large amounts of water. They are not well-structured soils. The structure is associated with a large number of fine and thick roots in the first horizons. They have dark colours ranging from black, dark gray, and dark brown in the first horizons. However, the colour is highly dependent on the mineralization rate of the large amounts of organic matter associated with these soils (Filipova *et al.*, 2010; Valle *et al.*, 2015).

Coverage and geographical regularities in the distribution. The geographical distribution of this wetlands meadows throughout all of Chilean Patagonia covers an area of around 2 600 ha of meadows in the province of Aysén, 8 500 ha in the province of Coyhaique, 3 800 ha in the province of Capitán Prat,

and 1 700 ha in the province of General Carrera, in the Aysén region (CONAF, 2006). In the Magallanes region, according to the Servicio Agrícola y Ganadero, the area of wetlands is 81 500 ha in the province of Tierra del Fuego, 105 700 ha in the Magallanes province and 51 800 ha in the Ultima Esperanza province, occupying 6.9 percent of the sector (SAG, 2003; SAG, 2004a; SAG, 2004b).

Land use and management. The wetlands described here are associated with livestock production in the Magallanes region. This activity was established in the second half of the nineteenth century, through large land grants by the State and an important bet of private companies (Strauch and Lira, 2012). In the Magallanes region, more than 56 ha of the sheep mass of the country and around 141 759 cattle (INE, 2007). The type of livestock is characterized by being extensive and continuous. This means that a large amount of land area is required to support few animals, with the average stocking rate being one sheep per hectare.

Ecosystem services

- **Food, feed, and fibre production, these soils are mainly sustaining prairies destined for sheep and cattle.**
- **Water regulation, this type of ecosystem allows to solve the evaporimetric demands thanks to the large amount of water they accumulate (Ivelic-Sáez *et al.*, 2021).**
- **Biological diversity**
- **Climate change mitigation and adaptation**

Carbon stock and stability. Here, we summarize data published by Filipova (2011) and Valle *et al.*, (2015). See table 2.5.5.

Table 2.5.5 Carbon stock of different types of soils

Source: Filipová L. 2011. *Soil and vegetation of meadow wetlands (Vegas) in the South of the Chilean Patagonia*. Faculty of Science Department of Botany, University Olomouc. PhD dissertation and Valle, S., Radic, S. & Casanova, M. 2015. *Soils associated to three important grazing vegetal communities in South Patagonia*. *Agrosur*, 43(2): 89-99.

Soil Type (WRB)	Local Name	UTM coordinates	Deep (cm)	tonnes C /ha
Haplic fluvisol	Cabeza de Mar 1	19F0071016;4160004	27	353
Parahístico gleysol	Campo El Monte-1	19F0067913;4162976	31	167
Haplic gleysol	El Álamo	19F0515511;4066613	53	108
Humic fluvisol	Quinta Esperanza	19F0401676;4147744	40	395
Haplic vertisol	Cerro Castillo		100	399
Gleyic solonetz	Laguna Blanca-1	19F0353128;4202000	41	89
Gipsyc solonchak	Laguna Blanca-2	19F0352595;4204986	38	104
Histic fluvisol	Domaike-2	19F0352157;4173300	20	239
Histic fluvisol	Estancia Springhill	19F0477297;4165874	64	149
Calcaric-Humic fluvisol	Parque-Josefina	19F0370477;4165476	90	963
Folic gleysol	Entrevientos	19F350365S;4170106	90	272

Major threats and degradation processes. In Patagonia, the wetlands meadows, are degraded by overgrazing, with signs of strong compaction due to trampling, reduction of plant richness, and invasion of exotic species. Overgrazing changes the structure of vegetation communities, allowing the dominance of indicator species such as *Caltha sagitata* in salty wetlands and *Azorella trifurcata* (Díaz Barradas *et al.*, 2001). This can be corroborated based on studies in Vegas prior to the introduction of sheep, where a low presence of the two species is mentioned (Dusén, 1905). Having prostrate growth, sclerophyllous leaves, the presence rhizomes, and other types of vegetative growth, allow *Caltha* and *Azorrella* to resist grazing, as they can better compete for light versus other taller species, but not very tolerant of continuous grazing (Díaz Barradas *et al.*, 2001). In oil exploitation areas, there is threat of contamination by hydrocarbons (Collantes and Faggi 1999). In Tierra del Fuego, overgrazing sheep and trampling interact with the strong winds of the Fuegian steppe, constituting the main agent of degradation of the wetland's soils (Iturraspe and Urciuolo, 2000). Furthermore, in many cases, drainage has caused the formation of deep cracks that then prevent the use of paddocks as pastures, with the exclusion of sheep then promoting the growth of competitively strong grass species (Filipova, 2011). The progressive degradation of these types of soils has resulted in the reduction of animals by 16 percent (INE, 2014) since 2007.

Colombia

Black soils in highlands. The parental material has played a very important role in the formation and evolution of moorland soils, despite being considered a passive factor in the edaphogenetic process. In the central and western Cordilleras, and in some areas of the eastern Cordillera, soils have been developed from the weathering of volcanic ash. In the highest part, above 3 800 metres, the volcanic glass is not altered (Vitric Andosols), while between 3 200 and 3 800 metres they are more differentiated (Aluandic and Silandic Andosols, some of them Gleyic). In the definition of these characteristics, low temperatures and relatively young soils play a fundamental role (Morales *et al.*, 2007). In the eastern Cordillera (within the Sumapaz area), partly on calcareous and ashless rocks, there are soils of the reference groups Leptosols and Cambisols, and organic skeletal and, locally, very organic soils (Histosols). Above 3 800 metres above sea level, where low temperatures are a dominant factor, there are Cryosols. In the Sierra Nevada de Santa Marta, Gleysols

are found on igneous rocks above 3 800 m and at least up to 4 100 m. When the climate is very humid, peaty soils with very high organic matter content develop in the paramos depressions, in part related to swamp or peatland vegetation types (Sapric, Hemic and Fibric Histosols) (Morales *et al.*, 2007).

Two main factors determine the soil type and properties: 1) the climate; and 2) the existence of a homogeneous layer of volcanic ashes from quaternary volcanic eruptions (Winckell, Zebrowski and Delaune, 1991). A cold and wet climate low atmospheric pressure favor organic matter accumulation in the soil. This accumulation is further enhanced by the formation of organometallic complexes strongly resisting microbial breakdown (Nanzyo, Dahlgren and Shoji, 1993). The resulting soils are dark and humic with an open and porous structure.

The higher values of SOC under natural vegetation are due to the greater protection of the soil surface provided by the type of vegetation cover (Castañeda-Martin and Montes-Pulido, 2017). For example, sites with dense cover such as bryophytes and shrub species that isolate soil from factors such as precipitation and direct incidence of solar radiation, may present greater amounts of SOC because there is less decomposition of organic matter. Also, the higher root density characteristic of these plants can influence the high SOC values. While soils under more dispersed cover, such as natural grasses of the *Asteraceae* and *Poaceae* families and *Pteridophyta*, may contribute less subsurface biomass to the soil and facilitate greater organic matter decomposition (Zimmermann *et al.*, 2010).

Over time there has been an interaction between the moorland ecosystem and the inhabitants of these territories, but at present, this interaction has changed dramatically (Cárdenas, 2013; Sarmiento and Frolich, 2002). In ancient times, the moors were sacred regions for pre-Columbian cultures, who only used them for rituals of worship and offering to their gods, since they were conceived as the place where the ancestors rested. During the time of the conquest and the colony, the arrival of new animal species, like cattle, altered the ecological dynamics in the places where this type of grazing was consolidated, such as the lower regions with better climatic conditions. Due mainly to the lack of land in local communities, the high population growth, and the inequity in land tenure, in the last century the slopes of the mountain ranges were colonized discovering the agricultural possibilities of the moors (Hofstede, 1995; Hofstede, 2001). To all this, we must add the increase in pine plantations, the increasingly evident effects of climate change, and the conflict with

armed groups (Cárdenas, 2013). The fresh herbs of moors provide ideal locations for grazing (Hofstede, 1995) and to encourage the growth of fresh grasses, native vegetation including xerophytic shrubs are often burned before being used for grazing. As a result, the combination of grazing and regular vegetation burning activities has become a common management practice to support the growth of appetizing young grasses used for livestock feed (Hofstede and Rossenaar, 1995). At the same time, the most favourable areas related to the presence of black and deep soils are cultivated and used for potato and bean cultivation (Horn and Kappelle, 2009).

In natural moorlands hillslopes, little surface water erosion occurs on Andosols, but this behaviour changes when the natural vegetation is converted to agriculture due to intense mechanized tillage or conversion to pastures where trampling occurs (Dörner *et al.*, 2016). Cuervo-Barahona, Cely-Reyes and Moreno-Pérez (2016) found that native vegetation in the Cortadera moorland, Boyacá (Colombia) had a higher SOC content in relation to the cover crops of *Solanum tuberosum* and *Avena sativa*, and *Pennisetum clandestinum* grasses, possibly due to the low level of resilience of moorland soils, which when subjected to planting and grazing activities, tend to release a proportion of the carbon into the atmosphere through oxidation. Likewise, among the covers established for anthropogenic activities, grassland areas presented the lowest carbon content, which is probably because this activity has deep effects on the structure and functioning of the moorlands, where cattle trampling generates soil compaction and loss of physical, chemical, and biological properties that retain water and carbon (FAO, 2002).

The velocity of land use changes has been quantified at several locations. Van der Hammen *et al.*, (2002) quantified the land use changes in the paramo of Laguna Verde in Cundinamarca, Colombia. From 1970 to 1990, cultivation increased by 106 percent, grasslands by 164 percent. High altitudinal forests decreased by 32 percent. For the whole country, the increase in cultivated area in moorlands was estimated at 24.9 percent (Hincapié *et al.*, 2002). Land use changes in adjacent regions may also affect moorlands climate. Cloud formation in downslope montane cloud forests is assumed to sustain air humidity in upper mountain regions (Foster, 2001). Massive deforestation of the Andean slopes occurred during the last century and as a result, it may have altered the paramo climate (Buytaert *et al.*, 2006b).

Burning, intensive grazing, tilling, and replacement of the natural grassland with more nutritive grass species

significantly affect the water balance of the moorland's areas (Sarmiento and Frolich, 2002). Effects typically accompanying pasture farming and tillage, such as soil compaction and soil crusting, additionally alter the infiltration rates, water storage, and regulation capacity of moorlands. This seriously compromises its water supply function. Some scientists also state the effects of human activities in terms of accelerated soil erosion given the properties in moorlands (Poulenard *et al.*, 2001). Very few studies have been conducted to quantify the impact of these land management changes on the hydrodynamic properties of moorlands (Buytaert *et al.*, 2006a), their floristic composition, the vegetation structure (Morales *et al.*, 2007), the morphological evolution of soils (Poulenard *et al.*, 2001) or on carbon storage in soils (Zúñiga-Escobar *et al.*, 2013).

Currently, there is an extension of potato, pea, and bean farming and cattle raising in almost all of the moors, even within some natural national parks. There are sufficient studies on the effects of these activities on vegetation, biodiversity, soils, and water (Van der Hammen *et al.*, 2002). In terms of agriculture, mainly potato cultivation is reaching higher and higher altitudes, approaching 4 000 metres above sea level (Morales *et al.*, 2007). Part of this corresponds to rotation crops, which originally could be left after a harvest to fallow for up to 20 years, but now, with agrochemicals, this period has been greatly reduced, which does not allow for proper regeneration of the vegetation (Morales *et al.*, 2007). In addition, the planting of introduced grasses has been extended, converting the moorland vegetation, little by little, into pastures. Every day there are fewer frailejones, which need between 50 and 100 years to reach a height of several metres again. At present, the moor is occupied by potato farmers, who buy or rent large areas and destroy the original vegetation completely with heavy machinery. The displacement of agriculture to higher altitudes is related to the development of potato varieties that are more resistant to frost and to the increase in temperature (Morales *et al.*, 2007).

Anthropic black soils. The Amazonian Dark Earths (ADEs) are anthropogenic soils created by inhabitants of the Amazon region between 2 000 and 500 years ago (Neves *et al.*, 2004), easily distinguished from natural soils by their chemical properties and other features observable to the naked eye such as their dark colour and their deep A horizon with the presence in most cases of potsherds, lithics, and charcoal pieces left by ancient anthropogenic activities (Kämpf *et al.*, 2003). Therefore, ADEs are classified as Pretic Anthrosols or

as anthropogenic soils (Peña-Venegas *et al.*, 2016). These soils have a structure similar to organic soils, which can be created naturally by fluctuations in aerobic levels in areas with high accumulation of organic matter or human-made (Teixeira and Martins, 2003). They are black to dark gray-brown soils, have a high content of available phosphorus, variable calcium and magnesium, and presence of ceramics. The greatest number of studies on ADEs have been of the anthropological type and little is known about their genesis (Woods and Mann, 2000).

About 70 percent of the Amazon basin is composed of mainly very acid, highly weathered natural soils with poor availability of the most important plant nutrients (Richter and Babbar, 1991). There are, however, small patches of anthropogenic soils known as ADEs with completely different characteristics: ADEs are usually less acid with better cation exchange capacity and base saturation than natural soils (Glaser *et al.*, 2001). ADEs also contain more nitrogen, calcium, available phosphorus (Lima *et al.*, 2002) and organic matter; the higher organic matter content results in ADEs having better moisture-holding capacity and lower rates of nutrient leaching than natural soils (Glaser and Birk, 2012). In the Colombian Amazon region, ADEs have been reported along the Caquetá river (Mora, 2003), along some small tributaries of the Amazon river (Morcote-Ríos and Sicard, 2012). Most of the indigenous inhabitants of the Colombian Amazon basin have access to both natural soils and ADEs. For the Middle Caquetá river region where most ADE studies have been conducted, reports show that Indigenous Peoples recognize ADEs as the most suitable soils for agriculture (Galán, 2003).

The characteristics of the Antrosols in the Amazon have led several experts to suggest that these soils were made on purpose more than 1 000 years ago by Amazonian indigenous communities, to have the possibility of maintaining intensive crops for their sustenance. It is now known that these soils maintained permanent crops of *Manihot esculenta*, *Zea mays*, *Bactris gasipaes*, and *Mauritia flexuosa* (Peña-Venegas and Vanegas-Cardona, 2010).

2.5.5 Pacific

In the Pacific region, black soils occur in three main soils. The first group is swelling black soils (Vertisols) present mainly in Australia, where such soils cover about 15 percent of the national territory. It is important to note that Vertisols in Australia are not necessarily black: the national classification indicates also the presence of gray, brown, red and yellow

suborders of compacted soils (Isbell, 1991). However, the black colour is the most common one. These soils are widely used in agriculture both for producing grain crops, tropical cultures, and cotton. They have a good potential due to their richness in nutrients and good water-holding capacity. However, their physical properties, such as swelling and shrinking and their strong compaction in a dry state, are limiting factors for their use. Volcanic black soils are especially widespread in New Zealand but are also common in Oceania on the islands of volcanic origin. Papua New Guinea, the biggest island in Oceania, also has some mountainous slopes with volcanic black soils (Neall, 2009). These soils are intensively used in agriculture, though high P retention limits their productivity. On many small islands of Oceania on coral reefs Rendzina-like black soils on calcium-carbonate-rich material form. Though these soils are mostly shallow, local farmers use them for cultivating taro and yams. Cultivation of these soils, unfortunately, increases the mineralization of organic matter and the emission of greenhouse gasses to the atmosphere.

2.5.6 Near East and North Africa

In the Near East and North Africa (NENA) region, black soils are uncommon because of the arid and semi-arid conditions almost everywhere in this region. However, some of the places with Mediterranean climate can lead place to the formation of dark-coloured soil, mainly on limestone material. The Syrian Arab Republic is one of the countries where black soils have been described in the NENA region (FAO and ITPS, 2015).

Syrian Arab Republic

The importance of black soils in the Mediterranean regions comes from its rare occurrence in semi-arid environments (Tarzi and Paeth, 1975). Reifenberg (1947) suggested that the immaturity of these black soils derived from soft limestone due to erosion of disintegration products of soft limestone. Durand and Dutil (1971) showed the importance of the texture of soft and hard limestone in the development of both types of soils. Tarzi and Paeth (1975) found white Rendzina soils derived from soft Miocene and Senonien limestone, developed on the foothills of the Lebanon and Anti Lebanon Mountains. These soils usually have high available P, and CaCO₃ contents (Sayegh and Salib, 1969). Soils of the Syrian Arab Republic were mapped by Ilaiwi (2001). Two forming factors- parent material and relief- shape soil characteristics (colour, depth). The impact of parent material is reflected in the

emergence of different organic soils such as Rendzina on limestone, chalk, sandstone, conglomerates, and claystone. Reddish Rendzina on Dolomite and hard limestone. Grayish Rendzina on Serpentine. Calcic Kastanozems occur on calcic marl and lacustrine deposits. The impact of relief is clear on soil depth Rendzic Phaeozems occur on toe slopes and foot slopes, Rendzic Leptosols on shoulders, and deep Chernozems occur on a flat plains.

In some areas on the coastal plain as well as in Al Ghab plain, with 600 mm annual rainfall and xeric moisture and thermic temperature regime, soils have high SOC content as well as high carbonate content (Rendzic Phaeozems). These soils were developed from Calcaric Leptosols by humification. On shoulders and slopes, the mollic horizon is shallow (eroded), giving way to the formation of Rendzic Leptosol. This soil is relatively immature, not deep with one unique diagnostic mollic epipedon of 5 to 30 cm depth. The soil shows a strong reaction with dilute hydrochloric acid, which indicates the high content of calcium carbonate.

In the Al Ghab plain, black soils are associated with the extension of the great African faults along the eastern coast of the Mediterranean. Before their recent artificial drainage, most of these areas were annually flooded; ponding of plains last two months (January to February). These soils were developed over marl, freshwater organic, woody materials conglomerates of lacustrine deposits and lacustrine deposits (El Ghab, Amuq), marl, freshwater organic of lacustrine deposits, and basalt (Hala Homs, Hala Galilea). These soils are mollic with or without cambic horizon below the epipedons or of a calcic horizon within 1.5 m of the soil surface are the main reasons for the soil complexity.

There is no special use of these soils, but they are rather similar to other lands. In the coastal plains, they are devoted to cultivating citrus trees and protected crops, and in the Al-Ghab plain are cultivated with field crops (wheat, cotton, sugar beet, tobacco). Because of the availability of water, a part of the land is also devoted to agro-fishery.

Soils from the Syrian Arab Republic suffer degradation and depletion because of wrong practices and the lack of suitable laws to preserve them. The most important factors of deterioration and depletion include salinization because of irrigation with agricultural drainage water, pollution resulting from irrigation directly with untreated water sewage, decline of fertility due to using exhausting crops without using rational agricultural rotation, rapidly decaying of organic matter due to the wrong agricultural practice (organic matter has decayed from average 10 to less than 2 percent

during five decades), and urban encroachment on these exclusive lands because of the increase in population and lack of urban planning (FAO and ITPS, 2015).

2.5.7 North America

Canada

In Canada, black soils develop under a Cool Temperate Dry climate. In the Canadian soil taxonomy, these soils are named Orthic Black Chernozem, which corresponds to Udic Haplocryolls in the US Soil Taxonomy and Haplic Chernozems in the WRB. In the Black Chernozem zones, grasses become taller and denser, producing more biomass and hence more organic matter accumulates of about 5 to 6 percent, but it can go up to 8.5 percent. This would be equal to 210.2 Mg C/ha. Stable isotope of carbon is $-25.3 \delta^{13}\text{C} (\text{‰})$ for which about 90 percent is C_3 and 10 percent is C_4 plants. C_3 plants such as *Stipa comata* ($\delta^{13}\text{C}$ of -25‰), *Agropyron smithii* ($\delta^{13}\text{C}$ of -28‰), *Agropyron trachycaulum* ($\delta^{13}\text{C}$ of -28‰), *Stipa viridula* ($\delta^{13}\text{C}$ of -27‰) (Waller and Lewis, 1979), *Artemisia sp.* ($\delta^{13}\text{C}$ of -28‰) (Bender, 1971), *Populus tremuloides* ($\delta^{13}\text{C}$ of -27.2‰), *Pinus banksiana* ($\delta^{13}\text{C}$ of -26.6‰), *Rosa acicularis* ($\delta^{13}\text{C}$ of -27.9‰), *Fragaria virginiana* ($\delta^{13}\text{C}$ of -31.7‰) (Brooks *et al.*, 1997), and C_4 plants such as *Bouteloua gracilis* ($\delta^{13}\text{C}$ of -13‰). The amount of organic C to 120 cm depth on average is about 14.88 g/m. Colour 10YR Chroma is darker than 1.5 and value is less than 3.5. Lower temperature causes a slower decomposition of residue, and there is a possibility of leaching of organic matter from the soil system. Chernozems are dominant in the grassland regions of Canada including the great expanse of the Canadian Prairies. Soils presented here contains carbonates, especially accumulation of secondary carbonates. The pH values for the Ah horizons of the Chernozemic soils are neutral to mildly acidic. Black Chernozems contain high amount of soluble salts. They develop in parent materials ranging from coarse sands through to fine textured silts and clay loams. Parent materials that include significant amounts of marine shales are often higher in sodium. The major soluble cations are Ca^{2+} with Mg^{2+} , and Mg^{2+} increasing with depth. Major soluble anions are SO_4^{2-} and HCO_3^- . Major exchangeable cations are Ca^{2+} and Mg^{2+} . The time for soil formation since deglaciation, estimated to be 12 000 years before present, based on the deglaciation history of the prairies (Landi *et al.*, 2003a, b; 2004). A description of a typical profile of such soils is presented in Table 2.5.6.

Table 2.5.6 A description of a typical profile of such soils

Source: Landi, A., Mermut, A. R., & Anderson, D. W. 2003a. *Origin and Rate of Pedogenic Carbonate Accumulation in Saskatchewan Soils, Canada*. *Geoderma*, 117:143-156.
 Landi, A., Anderson D. W. & Mermut A. R. 2003b. *Organic carbon storage and stable isotope composition of soils along a grassland to forest environmental gradient in Saskatchewan*. *Can. J. Soil Sci*, 83: 405- 414.
 Landi, A., Mermut A. R. & Anderson, D. W. 2004. *Carbon Dynamics in a Hummocky Landscape from Saskatchewan*. *SSSAJ*, 68: 175-184.

Thickness of A horizon	12 cm
Soil texture	Mainly loamy
Soil structure	Granular and friable in the A and prismatic in B horizons
Soil porosity	All types of tillage provide a good soil porosity to soil at the time of seedlings
Soil colour	10 years < 3.5

As one can see from the description, the thickness of the topsoil A horizon is not sufficient for the criteria for mollic horizon in Soil Taxonomy and WRB. However, in Canada these soils are recognized for their high productivity and thus we include them in the concept of black soils.

Distribution of Black Chernozems in Canada is shown in the Global Black Soil Distribution map (FAO, 2022a). Based on organic matter content and also precipitation, very clearly identifiable zones exist from north to south following the precipitation line and organic matter content in the soil. Soil colour changes from absolute black to dark brown and brown. Anyone working in the field can see the soil colour change when travelling, from north to south in Saskatchewan. This is similar to Dokuchaev's zonality in the Russian Federation. The main controlling characteristic of the climate is, however, the substantial water deficit that occurs in the region. In central and western Europe, the distribution of soils equivalent to Canadian Black Chernozems is commonly found in areas dominated by forest vegetation (Eckmeier *et al.*, 2007).

The Canadian grassland regions have undergone an almost complete conversion to agricultural production since European settlement began in the 1870s. The water deficit limits agricultural production to small grains, oilseeds, pulse, and forage crops, and livestock production. The optimal soil density values were under different-depth cultivation to 25 to 27 cm with periodical loosening of soil to 50 cm (1.16 to 1.28 g/cm³). The effects of land use on soil physical and chemical properties varied with the intensity and frequency of disturbance. A reduction in soil C is one of the most widely reported effects of land use change and is thought to result from the removal of above- and below-ground biomass during the harvest of crops and from the increased oxidation of C_{Org} during tillage (Dodds *et al.*, 1996). If the cultivated toposequence as a whole is considered, the largest C losses were due to mineralization in lower slope areas and were more than

double the amounts lost by erosion at upper slope areas. In upper slope segments mineralization accounted for the largest portion of total C lost in the early years of cultivation, whereas erosion accounted for the largest portion in later years.

Conservation tillage has been a tremendous success story in Canada. However, decades of tilling have severely eroded the soil, removing topsoil from the knolls and slopes of hills. One option is adding cover crops and perennial forages to the rotation to build up organic matter in the soil. A more impactful solution is dragging soil from the bottom to the top of the hill.

Microbial abundance and diversity can be used to assess the relative impact of management on the long-term sustainability of cropping systems. Studies showed that tillage disturbance was not an overriding factor in determining microbial community composition in the long-term no-till (NT) and conventional till (CT) soils. Enhanced microbial activity in organically managed soils may make P more available. Livestock manures are rich sources of available phosphorus, but a majority of organic farmers in Canada do not keep livestock. Increasing management intensity of grasslands through planting more productive species or increasing fertilizer inputs generally increases SOC accumulation. Increasing the number of plant species or functional groups, especially when legumes are added, often increases SOC accumulation. Grazed grasslands generally accumulate SOC more rapidly than undefoliated grasslands. Grazed grasslands generally accumulate SOC more rapidly than undefoliated grasslands (Sollenberger *et al.*, 2019).

The prairies account for about 85 percent of Canada's arable land, making it the most important agricultural region of the country. Historically this region has been dominated by cereal grain production, especially hard red spring wheat. Crop production in the Canadian prairies is based on simplified monoculture input driven production of ecological annual crop production concept, considering the loss of organic matter and

natural and agricultural biodiversity to provide a level of economic stability for the farmers (Martens *et al.*, 2013). For example, after the big harvest of 2013 in the Canadian Prairies, a significant drop in nutrients resulted in increased fertilization in 2014.

Continuous crop and animal removal gradually reduces the availability of essential macro and micronutrients in the soil. Prairie soils do not have inexhaustible levels of any nutrient. The bigger the crop yields, the more plant essential nutrient are extracted from the soil. Soil depletion of the macronutrients such as N, P, K and S is more or less fully understood. Soil depreciation of plant essential micronutrients such as Cu, Zn and B are less well understood as we harvest crop after crop (Evans and Halliwell, 2001).

The adoption of crop diversification in the Canadian prairie agriculture for the period from 1994 to 2002, reflect its strengths and limitations for managing a variety of risks, including climate change. Based upon data from over 15 000 operations, it was determined that individual farms have become more specialized in their cropping patterns since 1994, and this trend is unlikely to change in the immediate future, notwithstanding anticipated climate change and the known risk-reducing benefits of crop diversification (Bradshaw *et al.*, 2004).

Major threats are the effect of cultivation and erosion on soils. Cultivated and virgin grassland soils were

compared on adjacent landscape segments in order to quantify losses or gains of organic C, N, P, and total P. Losses were generally greatest from the upper landscape segments where erosion resulted in significant reductions in solum thickness. Sediment accumulation through erosional processes and redistribution during tillage operations resulted in accretion on selected landscape segments along the cultivated fields. Soils derived from sandstone and siltstone appear to have lost larger proportions of organic C, N, and P through mineralization than the soils formed in shale. Mineralization losses of organic constituents were countered by accretion on depositional segments. Substantial reductions in N, in excess of the amount removed by grain and straw, occurred with continuing cultivation. Regression analyses indicated that losses of organic C, N, and P were more closely linked to erosion in the finer-textured soils formed in shale. Changes in total P were closely linked to redistribution and sorting of soil particles because the total quantity of P in soils is independent of mineralization transformation (Gregorich and Anderson, 1985). In 2011, the majority of farmland (74 percent) in Canada was considered to be at low risk from soil erosion. The risk of soil erosion has been decreasing on agricultural lands in Canada (Agriculture and Agri-Food Canada, 2011).



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United States of America

Geographical distribution. Climatically, the black soils of the United States of America are most abundant

in the IPCC climate zone Cool Temperate Dry, followed by Cool Temperate Moist, Warm Temperate Dry, Warm Temperate Moist, Tropical Moist, and least abundant in Boreal Moist (Figure 2.6).

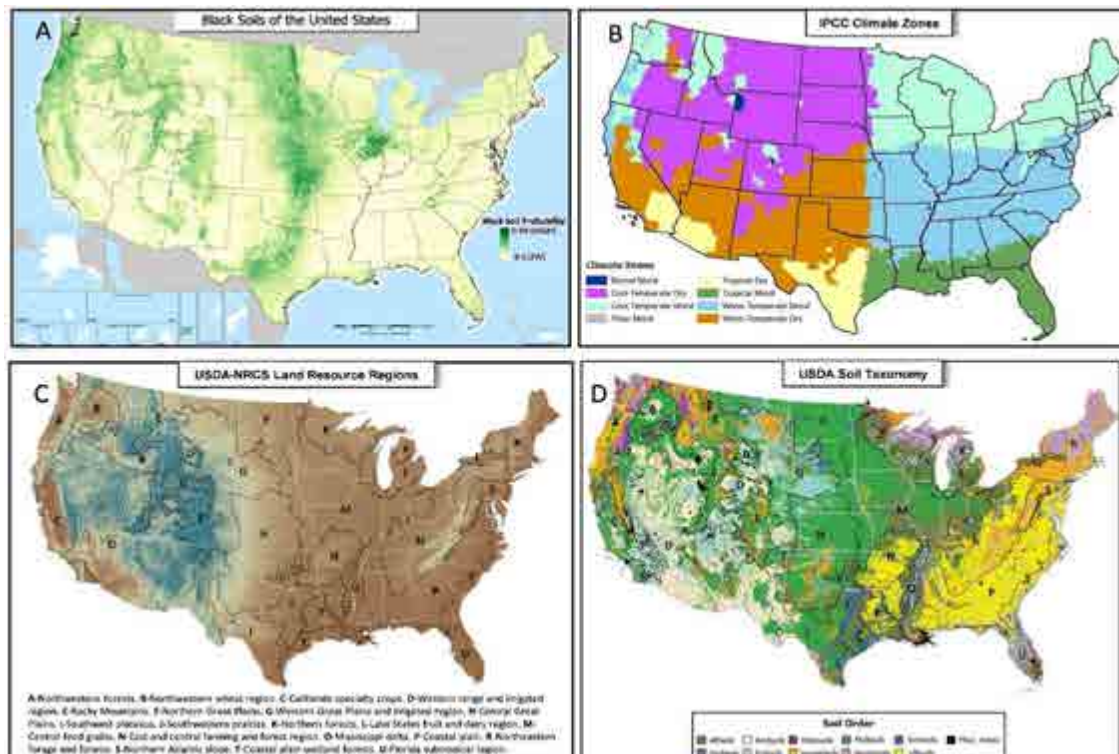


Figure 2.6 Comparison of black soils of the United States of America (A) with the IPCC Climate zones (B), USDA-NRCS Land Resource Regions (C), and USDA-Soil Taxonomy (D)

Source: Soil Survey Staff. 2014. *Keys to Soil Taxonomy*, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Classification of black soils using the World Reference Base for Soil Resources (IUSS Working Group 2015) and Soil Taxonomy (ST) (Soil Survey Staff, 2014) are listed in Table 2.5.7. The table is organized to show each USDA-NRCS Land Resource region (LRR) in which the black soils occur. (Compare Figures 2.6-A and C). Also listed in Table 2.5.7 are the subsection topics that pertain to the type of black soils: 1) black soils of midlatitude grasslands; 2) black soils of floodplains and wetlands; 3) Compact black soils; 4) Volcanic black soils; 5) black soils in tropics, and 6) Anthropogenic black soils.

Black soils in the United States of America are Mollisols formed under grassland vegetation in the High plains and Midwestern United States of America. The easternmost Mollisols formed under tallgrass prairie with a udic (i.e, humid climate) soil moisture regime and have less calcium carbonate in the subsoil than the Mollisols to the west that gain progressively more

calcium carbonate in progressively drier climates. The eastern tallgrass prairie Mollisols are Phaeozems in the WRB system and Udolls or Aquolls (if periodically saturated with water) at the suborder level in the ST system.

Westward across the Great plains, the tall grass prairie transitions into semi-arid steppes while simultaneously the udic moisture regime transitions into the ustic moisture regime. In this transition the Udolls transition into Ustolls and the Phaeozems transition into Chernozems then Kastanozems in progressively drier climates where black soils cease to be present.

Further westward, the black soils reappear in the mountains. With increased elevation, precipitation increases and the climate transitions from arid in the lowest elevations upward through grasslands, savannas, woodlands, and into evergreen forests. Black soils in the western mountains occur as Ustolls (Kastanozems and Chernozems) upward into the higher elevations until the

forest canopy closes. In the colder, higher elevations, black soils occur as Cryolls. Continuing west, the semiarid soil moisture regime shifts from Ustolls to Xerolls signifying that the seasonal distribution of precipitation has changed from spring and summer precipitation (ustic) to winter precipitation (xeric). Black soils also occur as volcanic ash soils (Andosols in WRB and Udands in ST) and Inceptisols (Cambisols in WRM and Xerepts in ST) in the westernmost states.

These black soil orders are minor in area compared to the Mollisols.

In the eastern United States of America, relatively minor areas of black soils occur as Histosols (Saprists and Hemists in ST), Podzols (Aquods in ST), and Vertisols (Usterts and Uderts in ST). In the southern Appalachian Mountains under temperate rainforest conditions, black soils occur as Cambisols (Udepts in ST).

Table 2.5.7 Soil classification of black soils as they occur in the Land Resource Regions (LRRs) of the conterminous United States of America

Source: Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC. Note the absence or very minor occurrence of black soils in Alaska, Hawaii, and The United States of America Territories (Figure 2.6A).

Land Resource Region	Black Soil Classification WRB Reference Soil Groups	Black Soil Classification Soil Taxonomy Suborders	Subsection Topic Category
A	Andosols > Cambisols > Chernozems	Udands>Udepts>Xerolls	Volcanic
B	Kastanozems	Xerolls	Midlat. Grasslands
C	Kastanozems	Xerolls	Midlat. Grasslands
D	Kastanozems > Cambisols	Xerolls, Xerepts, Ustolls	Highlands
E	Kastanozems>Chernozems>Cambisols	Ustolls, Ustepts,	Highlands
F	Chernozems, Kastanozems	Ustolls	Midlat. Grasslands
G	Kastanozems	Ustolls	Midlat. Grasslands
H	Chernozems, Kastanozems	Ustolls	Midlat. Grasslands
I	Kastanozems	Ustolls	Midlat. Grasslands
J	Vertisols, Chernozems	Usterts, Ustolls	Midlat. Grasslands
K	Histosols	Hemists, Saprists	Wetlands
L	Chernozems	Udolls	Midlat. Grasslands
M	Phaeozems	Udolls, Aquolls	Midlat. Grasslands
N	Cambisols	Udepts,	Highlands
O	Histosols	Saprists	Wetlands
P	(Very minor occurrence)	(Very minor occurrence)	NA
R	Podzols	Humods	Highlands
S	(Very minor occurrence)	(Very minor occurrence)	Highlands
T	Vertisols, Histosols	Usterts, Saprists	Wetlands
U	Histosols, Podzols	Saprists, Aquods	Wetlands

Peculiarities in genesis and properties. Major factors controlling the soil genesis for black soils in each LRR is listed in Table 2.5.8. Also shown is the predominant land use, the geogenic layers and pedogenic horizons in the soil that impart restrictions to roots, and the

carbon stocks, both organic and inorganic (CaCO₃). The carbon stocks are given for the whole area of the LRR in which the black soils occur. Thus, carbon concentrations in the black soils themselves will be higher than the values shown.

Table 2.5.8 Major factors controlling black soil genesis, land use of black soils, root-restrictive layers and soil horizons, and carbon stocks for the Land Resource Regions in which the black soils occur. Items in the table are listed in order of abundance if more than one item pertains

Source: Guo, Y., Amundson, R., Gong, P. & Yu, Q. 2006. Quantity and Spatial Variability of Soil Carbon in the Conterminous United States. Soil Sci. Soc. Am. J, 70: 590-600.

Land Resource Region	Black Soil Genesis	Black Soil Land Use	Black Soil Geogenic Restrictions	Black Soil Pedogenic Restrictions	LRR† Organic C Stocks tonnes C/ha	LRR† CaCO ₃ -C Stocks tonnes C/ha
A	Temperate rain forest	Evergreen forest	Paralithic, lithic	Cemented hrz, ortstein	142	0
B	Mountain forest soils	Evergreen forest	Paralithic, lithic	Duripan	78	79
C	Mountain forest soils	Evergreen forest	Paralithic, lithic	Duripan	101	4
D	Mountain forest soils	Evergreen forest	Lithic, paralithic	Duripan	44	91
E	Mountain forest soils	Evergreen forest	Lithic, paralithic	-	79	37
F	Tall grass prairie steppe	Soybeans, corn, wheat	Paralithic	Natric	137	119
G	Steppe, mountain soil	Grassland, Evergreen Forest	Paralithic, lithic	Natric	60	71
H	Steppe and prairie soils	Corn, cotton, grassland/pasture	Densic bk, lithic, Abrupt	Natric, petrocalcic	110	166
I	Savana and steppe soil	Shrubland, cotton	Lithic, densic bk	Petrocalcic	100	348
J	Tall grass prairie	Grassland/pasture, corn	Densic bk, lithic	Petrocalcic	118	296
K	(Very minor), bog soils	(Very minor), wetland	(Very minor) densic	(Very minor), fragipan	252	66
L	(Very minor), Bog soils	(Very minor), corn, wetland	(Very minor) densic	(Very minor), ortstein	209	117
M	Tall grass prairie on till	Corn, soybeans	Densic mtl, abrupt tex.	-	163	92
N	Temperate rain forest	High-elevation mixed forests	Paralithic	-	60	1
O	Flood plain deltaic soils	Wetland	-	-	109	21
P	(Very minor) marl prairie	(Very minor)	(Very minor), paralithic	-	91	1
R	Boreal forest soils	Mixed forest	Densic mtl, lithic	Ortsein	139	3
S	(Very minor) Mountain soil	(Very minor), mixed forest	(Very minor), lithic	(Very minor)	75	0

Land Resource Region	Black Soil Genesis	Black Soil Land Use	Black Soil Geogenic Restrictions	Black Soil Pedogenic Restrictions	LRR† Organic C Stocks tonnes C/ha	LRR† CaCO ₃ -C Stocks tonnes C/ha
T	Marl and bog soil	Wetland	-	Natric	353	24
U	Bog soils	Wetland	Lithic, paralithic	Ortstein	396	10

Note: † Midpoint estimate for the entire LRR from Guo *et al.*, 2006.

Black soil genesis follows three pathways. Most abundant is the addition of organic matter via decomposition of fibrous grass roots. This process (melanization) is responsible for most of the black soils in the United States of America. Second is the organomineral complexes between organic matter and minerals in Andisols and Vertisols. In Andisols, the complexes occur between organic matter and the short-range-order minerals like allophane and imogolite that weathered from volcanic ash (Soil Survey Staff, 1999). This process occurs in the northern regions of LRR A and E. In Vertisols, the complexes occur between organic matter and highly charged 2:1 clay minerals, primarily smectite. This occurs in the Blackland Prairies of LRR J. The third pathway is the concentration of organic matter resulting from curtailed fungal decomposition under anaerobic conditions when soils

are submerged in water. This occurs in the wetlands of LRR T, U, and K.

Soil textures vary widely in the black soils of the The United States of America primarily because the mollic epipedon, which is responsible for most of the black soils, is superimposed on numerous parent materials, including loess, glacial till, lacustrine sediments, alluvium from floodplains and fans, volcanic ash, and residuum from a multitude of sedimentary, metamorphic, and igneous bedrock. The structure of the mollic epipedon is typically “granular.” The subsoil structure, however, varies as a function of parent material and the degree of soil formation, ranging from “structureless” to “strong angular blocky.” The dark colour requirements are those of the mollic epipedon (Soil Survey Staff, 2014). The melanic and histic epipedons of the other black soils are similarly dark.



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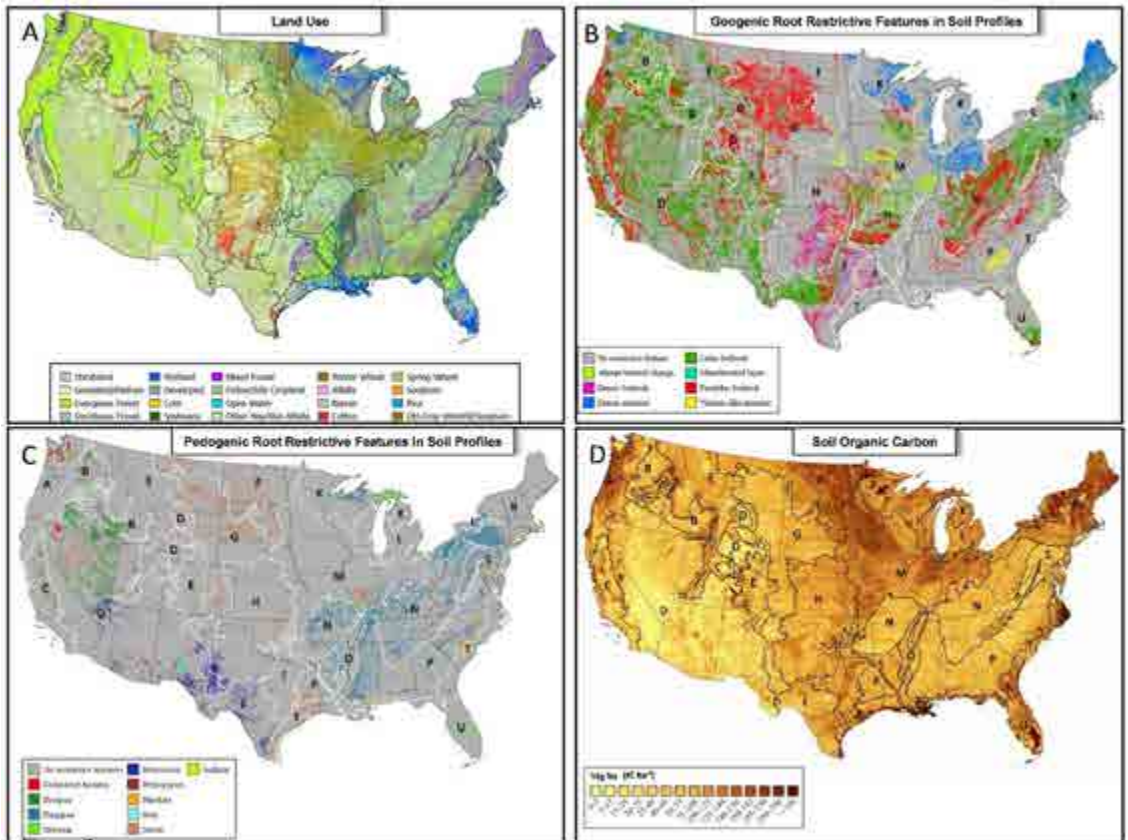


Figure 2.7 Land use, the distribution of root-restrictive layers and horizons, and SOC in the conterminous of the United States of America

Maps courtesy of Chad Ferguson, Natural Resources Conservation Service

Source: Soil Survey Staff. 2014. Keys to Soil Taxonomy, 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Note: The designations employed and the presentation of material in the map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

Regarding soil depth, Figure 2.7-B shows the distribution of geogenic layers that are restrictive to roots within 2 metres. Those impacting black soils include bedrock (lithic), weathered bedrock (paralithic, such as saprolite), abrupt texture changes, densic bedrock (such as soil fabric from weathered sedimentary rocks that prohibits the entrance of roots), densic material (such as compact glacial till) (Table 2.11). In addition to geogenic layers, pedogenic horizons that impose chemical and physical restrictions to roots are shown in Figure 2.7-C. Those impacting black soils include duripans, natric horizons, petrocalcic horizons, fragipans, ortstein, and cemented horizons (Table 2.11).

Coverage and geographical regularities in the distribution. Black soil distribution within the Land Resource Regions (LRRs) of the United States of America can be seen by comparing Figure 2.6-A and Figure 2.6-C. LRR-M contains the greatest amount

of black soils followed by the other LRRs with native prairie soils: (F, H, J, and I). The western LRRs with mountains (E, D, and A) follow with an abundance of black soils. Conversely, the LRRs with few or no black soils are LRRs P, K, and S. Similarly, Alaska, Hawaii, and the United States of America have few or no black soils (Figure 2.6-A).

Land use and management. Land use in the conterminous United States of America is shown in Figure 2.7-A. The land use of black soils is listed in Table 2.11. In LRR M, row crops, mainly corn (maize) and soybeans, occupy almost all black soils. Similarly, the black soils of LRR F and H are predominately used for corn and soybeans. Cotton and wheat are common crops grown on black soils of LRR H. The other black soils are used as grassland/pasture, forest, and wetlands.

Ecosystem services. Food, feed and fibre production is the primary use of black soils in the United States of

America. This occurs primarily in the midwestern and Great plain states of LRR M, F, and H.

Water regulation is a major ecosystem service of the black soils in LRR-R which is the location of several major cities (such as New York city). Likewise, water regulation is a very important ecosystem service for the black soils in the western mountains of LRRs A, B, C, D, and E which supply irrigation water and municipal water to the agricultural lands and cities in the drier lowlands.

Biological diversity is less important for the black soils of the croplands, although protection and restoration of native prairies does exist in a few areas, but it is of major importance for the black soils of the wetlands and mountains.

Climate change mitigation and adaptation pertains primarily to carbon sequestration, both organic soil and inorganic carbon. Essentially all the black soils used for cropland have lost substantial amounts of SOC. Consequently, these soils now have a high potential for sequestering carbon as a negative emissions technique while simultaneously improving soil health (Lal *et al.*, 2021). Carbon sequestration as inorganic carbon (CaCO₃) in black soils also holds high potential as a negative emission technique for the black soils of drier regions (Monger *et al.*, 2015a).

Other benefits of black soils include ecotourism for those in wetland, aesthetic and recreational benefits for black soils in western mountains, and scientific discovery for all black soils.

Carbon stock and stability. The distribution of SOC concentrations is shown in Figure 2.7-D and listed in Table 2.11. The values in Table 2.11, however, are mean values for the LRR as a whole, not just the black soils themselves which will have higher values. The highest concentrations are for those LRRs that have black soils occurring as Histosols in bogs (LRRs U, T, L, and K). The lowest concentrations are for those LRRs that have no to very few black soils (LRRs P, S, and N) or that have black soils in mountains surrounded by large deserts and semiarid steppes (LRRs D, B, and G). The black soils of the croplands (LRRs M, F, and H) have intermediate carbon concentrations.

Stability of carbon ranges from being stable in the wetlands (assuming they remain wetlands) but less stable in the western mountains and cropland.

The western mountains are experiencing catastrophic fires and concomitant erosion as well as desertification involving the loss of grassland to invading woody shrubs. Croplands, which have lost much carbon since the beginning of industrial agriculture in the mid-twentieth century, may continue to lose carbon as long as yields remain high, owing to commercial fertilizers. The loss of carbon, however, may be ending, given the recent emphasis on soil health, carbon sequestration, and water pollution, especially algal blooms and high-visibility hypoxia zones in oceans.

Major threats and degradation processes. Black soils of the cropland regions are threatened by surface compaction, loss of soil organic matter and tilth, accumulation of salts, pollution by overuse of fertilizers and pesticides, soil wetness, flooding, water erosion, wind erosion in the drier climates with soils having lighter textures, and loss to urban development (USDA Ag Handbook, in press). Black soils of the mountains are threatened with water erosion on the steeper slopes, overgrazing, the spread of invasive plants, especially noxious weeds, forest fires, soil sealing, loss of biodiversity, and desertification (Wang *et al.*, 2016; Monger *et al.*, 2015b).

The main drivers and pressures of soil degradation are improper land use and population growth. Climate change involving warmer and drier conditions is especially problematic for the black soils of the western mountains.

The status of soil degradation has been monitored by the USDA-Soil Conservation Service (now Natural Resources Conservation Service) since the 1930s. This agency is actively documenting indicators of soil degradation and health and promoting conservation efforts by working with farmers across the country.

Like soil degradation worldwide, the impact of soil degradation and human response in the United States of America are negative consequences for the farmers and the society on the whole, and the loss in natural capital. The efforts to mitigate soil degradation and restore degraded lands is urgently needed, especially with regard to food security, a broad range of environmental issues, and loss of biodiversity, and sustainable development goals of the United Nations (Lal *et al.*, 2021).



3. Status and challenges of black soils

3.1 A global overview of black soils

Although black soils account for only 8.2 percent of the Global Land Area (FAO, 2022a), they are of paramount importance for food security, as highlighted by the UN Sustainable Development Goal 2 (i.e. to end hunger, achieve food security and improve nutrition, and promote sustainable agriculture by 2030). The general category of black soils includes three main soil groups Chernozem, Kastanozem and Phaeozem, according to the World Reference Base for Soil Resources (WRB). Black soils are characterized by their thick, dark-coloured, and humus-rich topsoil. In general terms, black soils have granular and subangular blocky structure, optimal bulk density, and high amounts of plant nutrients. However all these favorable properties are only present in soils within virgin or quasi-pristine ecosystems, which are now rare (Montanarella *et al.*, 2021). There are other soil types also considered as black soils, as for example, swelling soils (Vertisols), volcanic soils (Andisols), anthropogenic soils, among others. Not all of them strictly comply with some of the conditions indicated for the Category 1 of black soil definition (such as having been formed under grassland vegetation) (FAO, 2019), but they all have some characteristics in their profiles that allow them to be classified as black soils, such as having a thick, dark-coloured, and humus-rich topsoil.

Apart from being highly productive lands, black soils are responsible for multiple ecosystem services such as water retention, maintenance of soil biodiversity from microorganism to megafauna, and soil fertility, and prevention of soil compaction and waterlogging. One of the most valuable services is accumulation of

great amounts of SOC in a relatively stable form. Black soils are one of the most important pools of carbon accounting for 8.27 percent (56 PgC) of the total global SOC stock in the top 30 centimetres of the soil (FAO, 2022d).

These carbon stores are, however, endangered by the processes of organic carbon loss due to the accelerated humus oxidation under cultivation. In many places the loss of humus and nutrient mining are the most important threats to black soils because these soils are considered as highly fertile “by nature” and thus have not needed application of organic and mineral fertilizers. Black soils are under further threat from various physical, chemical, and biological degradation processes (FAO and ITPS, 2015).

Some of these processes are easily reversible through sustainable soil management practices, such as nutrient imbalance, compaction, and structural degradation. However, other processes are difficult to reverse. First, soil loss due to erosion (wind, water and meltwater), is the most widespread threat in all world’s soils. Wind erosion is a problem that tremendously affected the Midwestern of the United States of America (the infamous Dust Bowl in the 1930s) and west Siberia and north Kazakhstan in the ex-Union of Soviet Socialist Republics (USSR) during the development of virgin lands in 1950s. Currently, soil salinization is becoming a growing problem, especially in irrigated areas in the most arid parts of the distribution of black soils. Second, land use change for food production exacerbates unsustainable management practices such as aggressive tillage and overgrazing furthering losses due to erosion. Diffuse pollution processes affect black soils devoted to fibre agriculture. This happens for various reasons, including the use of inappropriate fertilization technologies with high doses of nitrogen and phosphorus fertilizers and manures, or the excessive or inadequate use of herbicides and pesticides whose decomposition products are potential contaminants in soils, streams and groundwater. Finally, many black soils are threatened by soil sealing, due to the advance of urban areas and infrastructure in overpopulated regions or countries. This advance makes thousands of hectares of previously black soils destined for food production disappear.



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Photo 3.1 Black soil in Nenjiang county of Heilongjiang province, China



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3.2 Multiple benefits of black soils

3.2.1 Ecosystem services (ES)

Soils are involved in most of the ecosystem services (ES) that enable life on Earth, such as the provision of food, fibre, bioenergy, and water; the regulation of climate, gas, floods, droughts, land degradation, water quality, and pests and diseases; the support of nutrient cycles, and habitat for organisms; and the cultural non-material benefits such as recreational, spiritual, and religious values (See Figure 3.2.1a). Black soils have distinctive soil properties that are key for providing essential ES, for example, high soil organic matter contents and cation exchange capacities, better soil physical properties (soil structure, porosity, hydraulic conductivity, and infiltration) and habitats for soil

organisms, which ensure the provision of food, fuel and fibre and freshwater, the regulation of climate, erosion control and water purification, and the support of nutrient cycling (Adhikari and Hartemink, 2016).

Although all soils are responsible for and intervene in the provision of ES, black soils have a preponderant role in the provision of healthy food, nutrient and water reserves, habitat for organisms, among other functions. That is why the loss of organic matter due to unsustainable management practices is likely causes a greater impact than in other less fertile soils.

The linkages between soil and ecosystem services were represented by Adhikari and Hartemink (2016) through a diagram (See Figure 3.2.1a) that conceptualizes soils as a complex system which provides multiple benefits for the environment and society, and the need to study it in a holistic approach to understand the multiple interactions between soil functions, ecosystem services and human well-being.



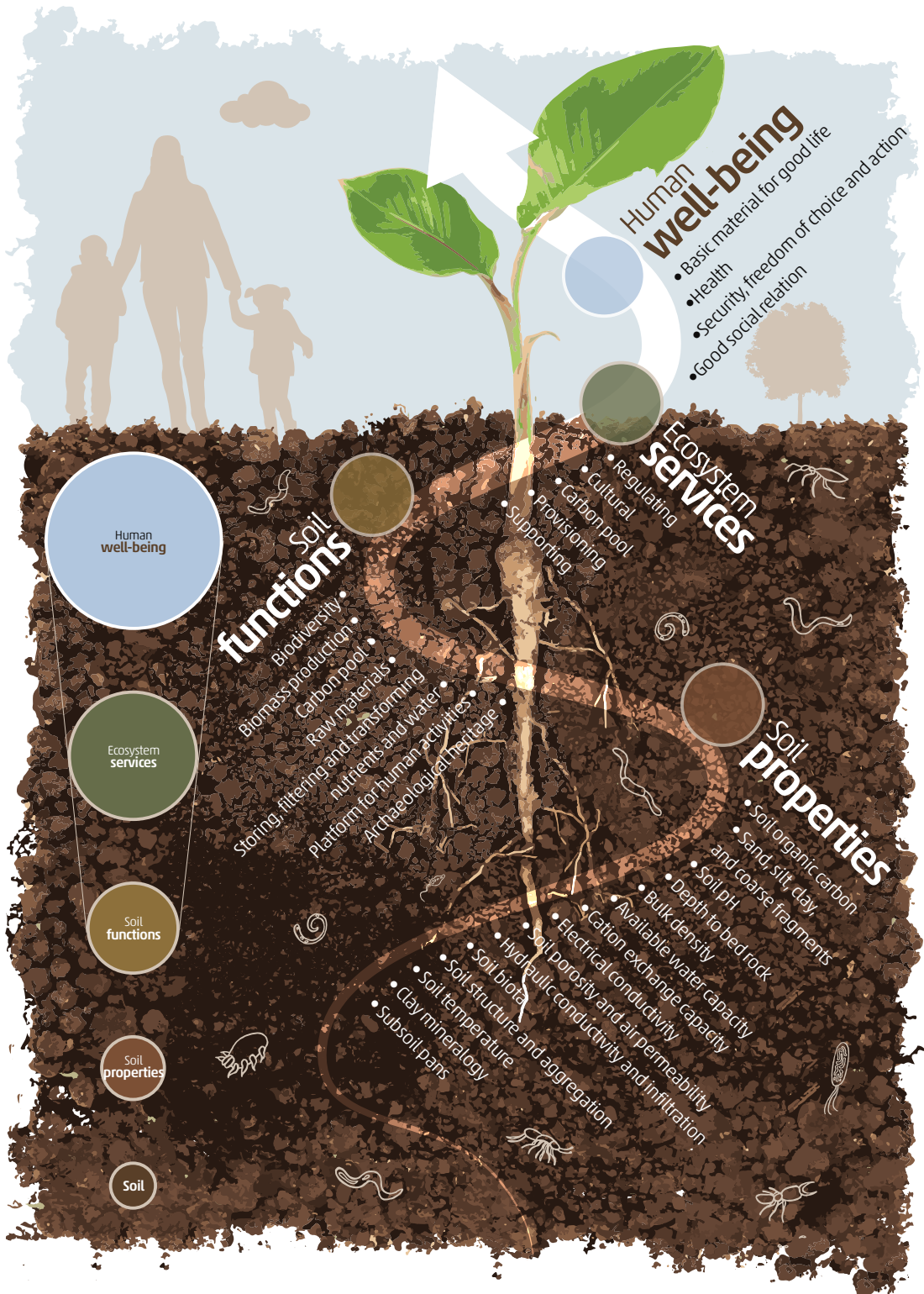


Figure 3.2.1a A conceptual diagram linking key soil properties to ecosystem services through soil functions for the well being of humans

Source: Adhikari, K. & Hartemink, A.E. 2016. *Linking soils to ecosystem services—A global review*. *Geoderma*, 262: 101–111. <https://doi.org/10.1016/j.geoderma.2015.08.009>

Anthropic soil erosion driven by conversion of natural ecosystems to agroecosystems and mechanical tillage, has numerous adverse impacts on ecosystem services. There are: 1) on-site impacts like the degradation of soil quality, reduction of agronomic productivity, and

the decrease in use-efficiency of inputs; and 2) off-site impacts like accelerated soil erosion that promotes eutrophication and contamination, and sedimentation of reservoirs and waterways, and emissions of CO₂, CH₄, and N₂O (Lal, 2014) (Figure 3.2.1b).

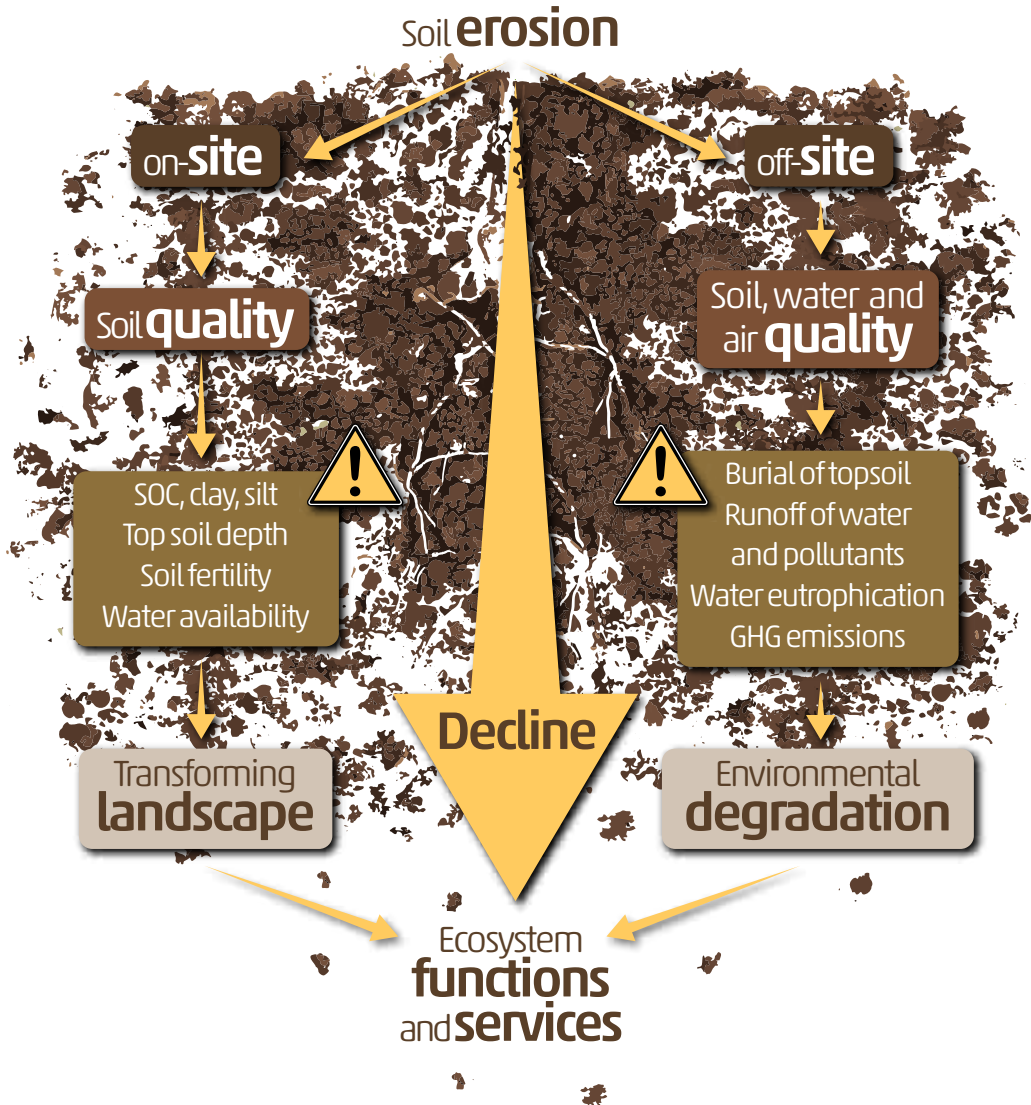


Figure 3.2.1b Adverse effects of accelerated erosion on ecosystem functions and services

Source: Lal, R. 2014. *Soil conservation and ecosystem services*. International Soil and Water Conservation Research, 2(3): 36-47. [https://doi.org/10.1016/S2095-6339\(15\)30021-6](https://doi.org/10.1016/S2095-6339(15)30021-6)

3.2.2 Climate change mitigation and adaptation

Black soils can contribute to both the mitigation of and adaptation to climate change. On the one hand, black soils have a high potential to mitigate climate change due to their high SOC sequestration potential (See Figure 3.2.2). According to FAO's Global Soil Organic Carbon map (GSOCmap), in the top 30 centimetres SOC stock of black soils is on average 56 PgC (or 77.24 tonnes C/ha), which is higher than the average of SOC stock in all mineral soils (FAO, 2022b). On the other hand, black soils have been cultivated since many centuries in Europe and Asia, and in the last 150 to 200 years in America and Oceania. After extensive and intensive cultivation (for cereals, pastures, ranges, and forage systems), black soils have significant losses of SOC (See Figure 3.2.2). According to various estimates, SOC loss of up to 50 percent of initial SOC occurred after conversion from a natural system to intensive farming, as happened in intensively cropped soils of the United States of America (Gollany *et al.*, 2011). This SOC loss results from of inappropriate land use and unsustainable management practices, leading to declining soil quality. The decline in soil quality is generally characterized by poor topsoil structure, increased soil erosion, resulting in emissions of carbon into the atmosphere exacerbating climate change (Lal, 2019).

Much of the carbon loss was caused using aggressive tillage systems, but also by the replacement of perennial vegetation (grasslands, forests) by annual crops, which in general generate lower carbon returns to the soil and hydrological imbalances (Fan *et al.*, 2017). When grasslands are converted to croplands, they lose on average 36 percent of their SOC stocks after 20 years (Poelau *et al.*, 2011).

Soil organic carbon sequestration represents 25 percent of the total potential of climate change mitigation

solutions (23.8 Gt of CO₂e per year) (Bossio *et al.*, 2020). Forty percent of potential solutions for climate change mitigation through soil carbon is to maintain the existing SOC stocks, and the remaining 60 percent is rebuilding the depleted SOC stocks. The historical loss of substantial amounts of SOC confers black soils a low enough baseline to achieve significant SOC gains on the path to recovery. Nature-based solutions based on SOC-centered sustainable management practices have multiples benefits, and no tradeoffs have been identified (Smith *et al.*, 2020). The major potential for SOC sequestration is in black soils devoted to annual crops. This potential is mainly due to the large yield gaps and/or large historic SOC losses (Amelung *et al.*, 2020). After an appropriate land use and soil management, these black soils can increase their SOC and improve their quality. As a result, the rise of atmospheric CO₂ can be mitigated in black soil regions (Liu *et al.*, 2012). In conclusion, sustainable use and management of black soils toward maintaining or increasing their SOC stocks could be key for climate change mitigation and adaptation.

Black soils will contribute to mitigation through increases in carbon by sequestration in their profiles resulting from the adoption of nature-based practices such as those reviewed by Smith *et al.*, (2020). Many of these practices, such as improved cropland management, improved forest management, and increased SOC content, are based on more intensification and do not create demand for more land conversion. This land productivity increase for food production can avoid emissions that would occur through expansion of the agricultural land area (Mueller *et al.*, 2012), or by reducing the greenhouse gas intensity of products (Bennetzen, Smith and Porter, 2016). Improved cropland, grazing, and livestock management have moderate carbon mitigation potential, although their impact can be high because of the high number of hectares that they occupy.

Black soils, a **sink** or a **source** of carbon?

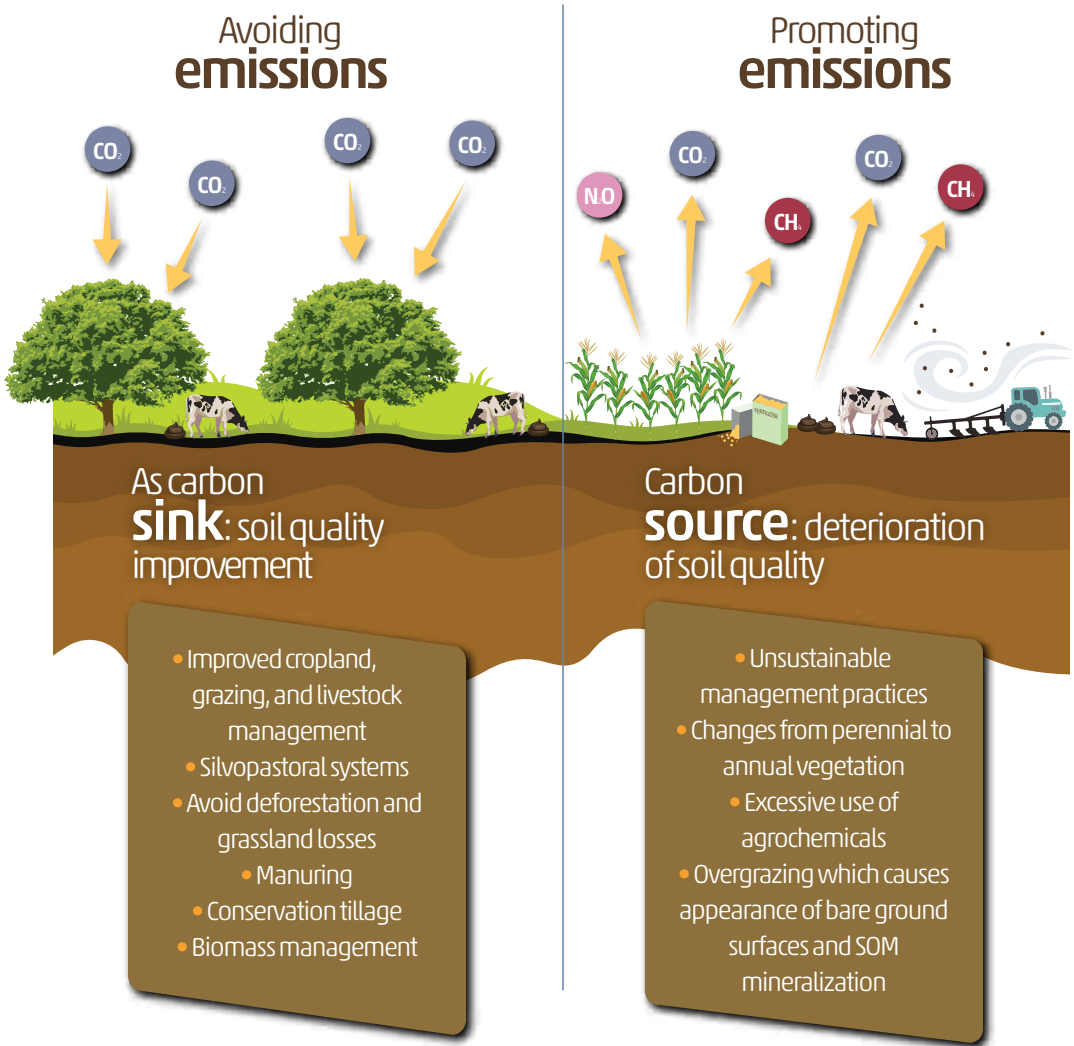


Figure 3.2.2 Duality of black soils as carbon sinks or emitters as a function of management practices

Source: Author's elaboration

3.2.3 Human well-being

Black soils contribute to human well-being by providing food security, filtering water, protection against chemicals and pathogens, and cultural ecosystem services (Brevik and Sauer, 2015) (See Figure 3.2.3). After hundreds of years of farming, black soils continue to be a symbol of healthy and nutritional food in many local cultures (Liu *et al.*, 2012). Black soils contain sufficient nutrients and provide nutritious food to people living there and in other regions, thus avoiding negative effects on human health (Steffan *et al.*, 2018).

There is evidence of the contribution of black soils made by ancient civilizations, as found in the Amazon region where pre-Columbian indigenous communities cultivated lowlands hundred years ago, left a legacy of charcoal, fish bones, and organic matter. The highly fertile soils, now called Amazonian Dark Earths evolved through these materials (Kern *et al.*, 2019; Anne, 2015; Schmidt *et al.*, 2014). Cultural values associated with black soils are observed in northeast China, where people associate them with healthy and positive characters to enhance the value of their personality, products, and culture (Cui *et al.*, 2017).



Multiple benefits of black soils

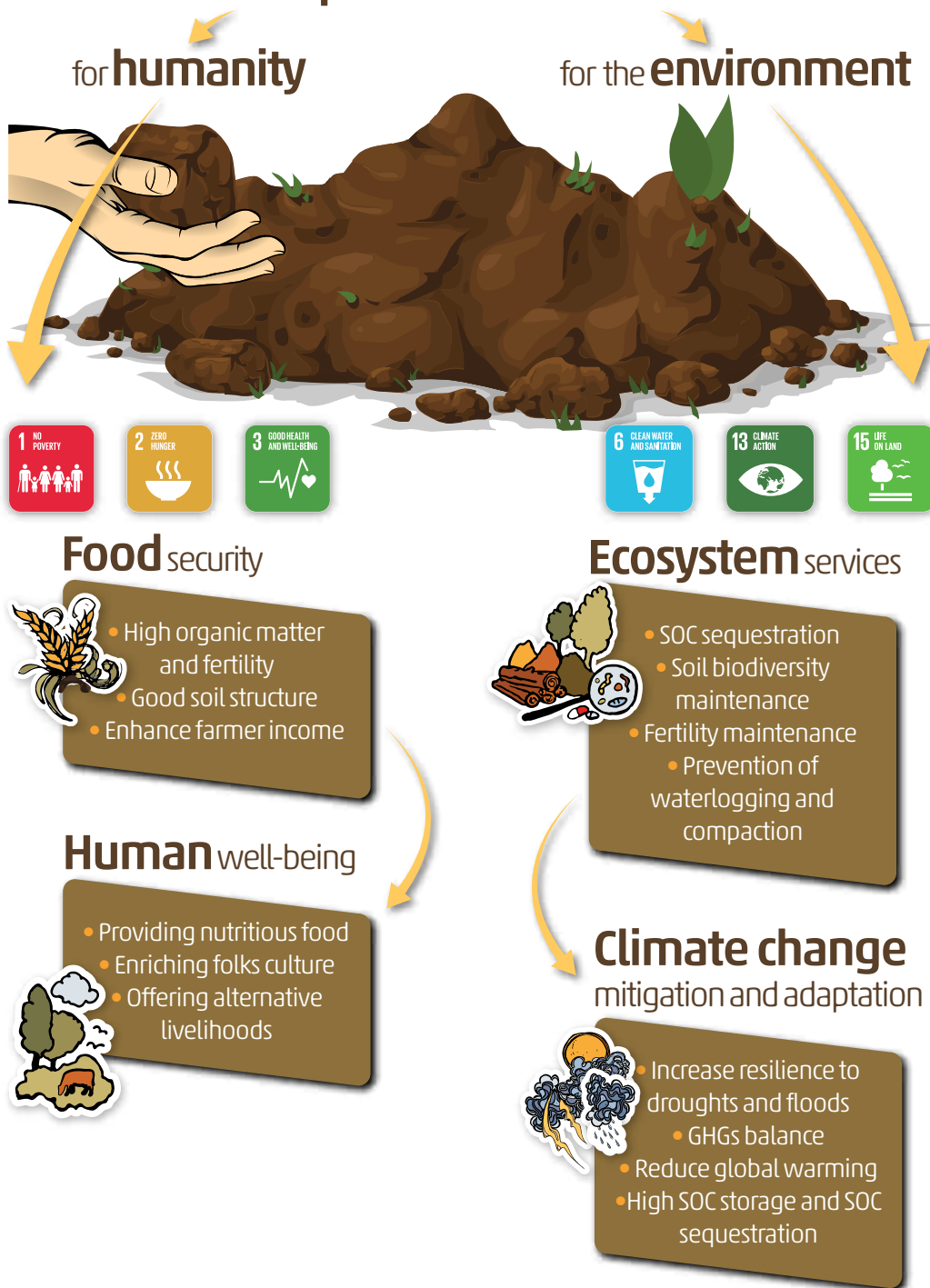


Figure 3.2.3 Multiple benefits of black soils

Source: Author's elaboration

3.2.4 Food production and food security

Global analysis shows that out of the total land dedicated to growing crops, 17 percent of the farmland is currently occupied by black soils (Chernozems, Kastanozems and Phaeozems) (IUSS Working Group WRB, 2006), and out of the total area covered by black soils, one third of the black soil area is used as croplands (FAO, 2022a), due, in part, to its inherent fertility. This high fertility often leads to underestimation of the risks of degradation, although these soils are strongly affected by irreversible degradation processes such as erosion, nutrient imbalance, compaction and structural degradation (FAO and ITPS, 2015).

In cold regions of east Europe and Eurasia, there are black soils with high inherent fertility (Chernozems). If the annual weather such as precipitation and temperature is supportive, these soils can ensure food security for the countries (Avetov *et al.*, 2011; Kogan, Adamenko and Kulbida, 2011; Kobza and Pálka, 2017). Food security is a national priority in China, a country where black soils are considered the food basket since the 1950s. They have been responsible for the production of 15.9 percent of rice, 33.6 percent of

maize, and 33.9 percent of soybeans in 2014 (Bureau of Statistics of China, 2015). In the United States of America, black soils cover 31.2 million hectares, and 42 percent of them are used for crop production (Soil Survey Staff, 2014; FAO, 2022a). In the southern cone of South America, most of the black soils sustain the production of grain and oilseed crops, orchards, forage, and crops for fibre production. They are also used for cattle raising and dairy farming, feeding the cattle with grains, forage crops or natural pastures (Durán, 2010; Durán *et al.*, 2011; Rubio, Pereyra and Taboada, 2019).

A set of international initiatives, such as the International Network on black soils, the 4 x 1 000 Initiative (Soussana *et al.*, 2019), and the framework of the Global Soil Partnership (Rojas *et al.*, 2016) have highlighted the need to maintain healthy soils and address threats to more fertile soils in order to cope with a 60 percent increase in food demand by 2050. Black soils are very fertile, and they are considered “the world crop basket” or “giant pandas in cultivated farmland” (Zhang and Liu, 2020) (See Figure 3.2.4). They are expected to receive increased use pressure in future decades that require better management practices and governance.



Black soils for food security

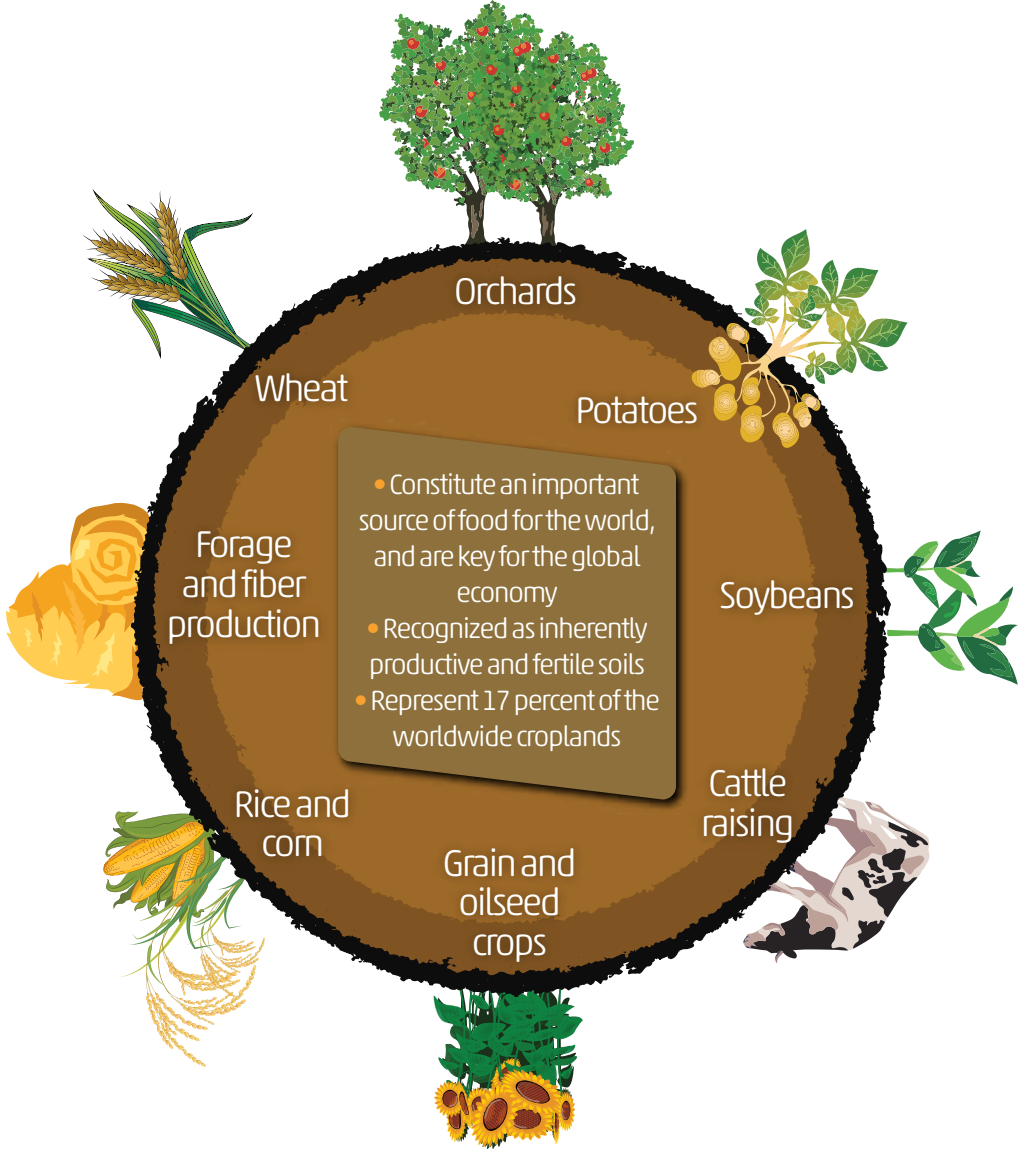


Figure 3.2.4 Black soils as a key player for global food security

Source: Author's elaboration

3.3 Main threats to black soils

The Status of the World's Soil Resources report (FAO and ITPS, 2015) highlighted the most significant threats to soil functions at the global scale, specifically soil erosion, loss of SOC and nutrient imbalance, and the current outlook is that this situation will worsen unless concerted actions are taken by all, the private sector, governments, international organizations and academia.

Black soils are not the exception and are affected by all global threats. As already mentioned, most of the cultivated black soils have already lost at least half of their carbon stocks and suffer from moderate to severe erosion processes, among other degradation processes. Other ongoing soil threats are soil nutrient unbalances, soil sealing and soil biodiversity loss (See Figure 3.3a).

World's soils are **under threat**

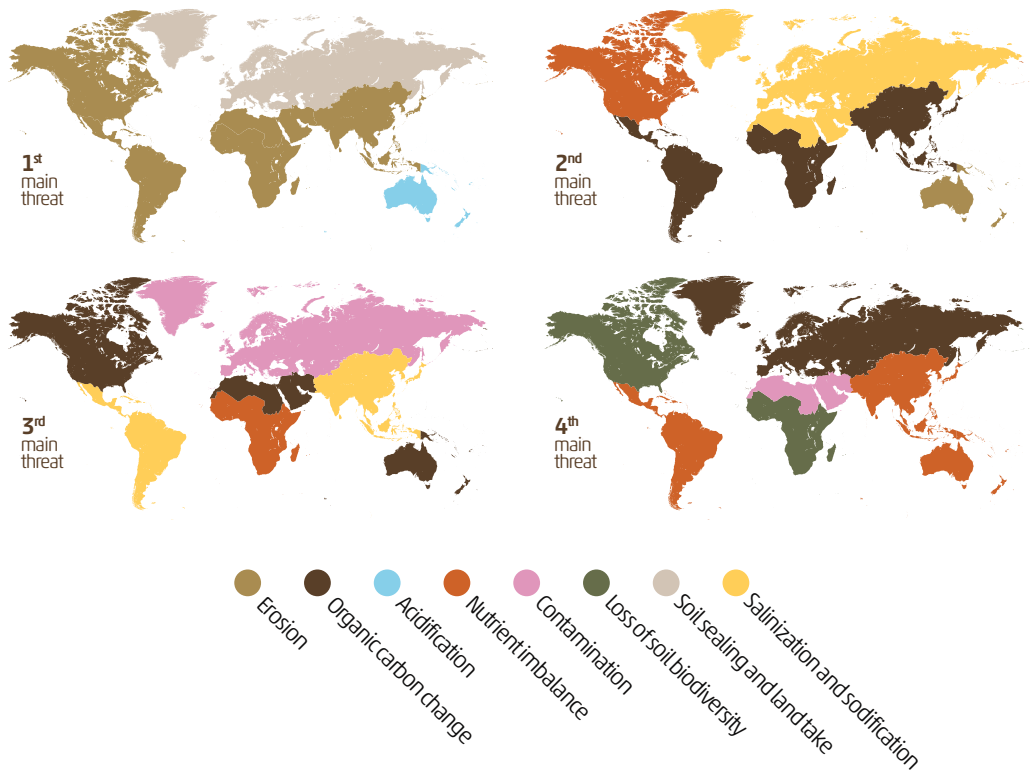


Figure 3.3a Global assessment of the four main threats to soil by FAO regions

Source: Montanarella, L., Pennock, D.J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Aulakh, m.s., Yagi, K., Hong, Suk Young., Vijjarnsorn, P., Zhang, G., Arrouays, D., Black, H., Krasilnikov, P., JSobocká, A., Alegre, J., Henriquez, C.R., Mendonça-Santos, M.L., Taboada, M., Espinosa-Victoria, D., AlShankiti, A., AlaviPanah, S.K., Elsheikh, E.A.E.M., Hempel, J., Arbestain, M.C., Nachtergaele, F. & Ronald V. 2016. World's soils are under threat. SOIL, 2(1): 79-82. <https://doi.org/10.5194/soil-2-79-2016>

3.3.1 Soil organic carbon loss

Land use changes and unsustainable management practices lead to generalized significant soil organic carbon (SOC) losses in black soils. SOC changes appear as the second main threat in South America due to deforestation, intensive cultivation of grasslands and monocultures, in northeast China due to land use change and degradation of grassland, and in Europe due to the replacement of the natural vegetation; all of these are regions where black soils are predominant or at least conspicuous (See Figure 3.3a).

The black soils of Ukraine provide a well-documented example of SOC loss. Since 1970 there have been significant changes in the reserves of organic matter in Ukraine. Average losses of SOC due to irrational land use over 140 years since the time of V. V. Dokuchae have reached 22 percent about 19 percent in the Steppe, and more than 20 percent in Polissya (Baliuk and Kucher, 2019).

According to Yatsuk (2015, 2018), the largest losses of humus occurred from the 1960s to 1980s, due to the intensification of agricultural production by increasing the area of row crops, especially sugar beets and corn. During this period, the annual losses of humus reached 0.55 to 0.60 tonnes/ha. These processes of soil dehumidification on agricultural lands continue. According to the results of agrochemical certification of agricultural lands during the last five rounds (1986 to 2010) the humus content in the soils of Ukraine decreased by 0.22 percent in absolute terms and is 3.14. In terms of soil and climatic zones, the largest decrease in humus content occurred in the soils of the steppe zone, dropping from 3.72 to 3.40 percent, (by 0.32 percent in absolute terms). In the Forest-Steppe these changes are slightly smaller but given the loss of humus are significant 0.19 percent. However, the dynamics of losses in the period up to 2015 is somewhat slowing down due to the introduction of new management practices (Yatsuk, 2018).

Studies from Canada also document the complex balance between organic matter additions and losses in black soils. In studies by Landi *et al.*, (2003 a, b, 2004), the net primary production of vegetation (NPP) of seeded forage grasses (based on dry matter) for the black Chernozems annual averaged about 490 g/m² for above ground and 206 g/m² below ground. The amount of organic C to a 1.2 m depth is nearly 150 MgC/ha. Annual average rates in the three soils studied 1.18 gC/M². Many researchers have suggested that prairie soils have lost about 30 percent of their organic matter under cultivation. The loss is estimated to be about 1.5 to 2 kg/m² by Mann (1986). Considering these losses

over 80 years of agriculture practices, the annual rate of loss is about 19 to 25 gC/m². This is ten to thirty times greater than the accumulation rate in the Black Chernozems. This rate is likely to be higher at the early stage of C losses and before levelling off and reaching. Therefore, it may take only a few hundred years to lose the majority of the SOC. Organic C in subsoils is older than the SOC in A horizon and, therefore, can represent a vegetation composition different than that of today (Mermut and Acton, 1984).

Losses of SOC can also occur due to grazing. In soils of the Anaime moorland (Tolima, Colombia) (between 0 and 30 cm deep) pastures in use stored SOC of 34.4 tonnes/ha, while pastures without use for 20 years stored 22 tonnes/ha. One explanation is the possible increase of biomass in the fine roots that when decomposed provide greater carbon content to the soil (Maia *et al.*, 2010), while lack of pasture renewal probably decreases the contribution of senescent roots (Andrade, Espinosa and Moreno, 2014). However, this aspect requires further study (Castañeda-Martín and Montes-Pulido, 2017). Avellaneda-Torres, Leon-Sícard and Torres-Rojas, (2018) and Otero *et al.*, (2011) found the behaviour of organic C showed a trend of moorlands > potato farms > cattle farms. Similar results were found in Chingaza natural national park (NNP) and Nevados NNP, where the C was lower in the soil profiles of conserved highland ecosystems than in non-conserved ecosystems. The decrease in easily oxidised organic C in soils under potato and cattle farming might have been caused by the loss of native vegetation cover due to cattle farming relative to the Paramo, which exposed the soil to environmental factors such as water, air, and solar radiation and likely increased erosion (Otero *et al.*, 2011).

Restoring SOC stocks in black soils via reasonable management such as conservation tillage, manure and compost fertilization, and biomass management is crucial to sustainable development and is important for environmental stability (Xu *et al.*, 2020). Among the causes of the decline in SOC are land use change, aggressive tillage, inadequate cropping system management (such as monocultures), and limited replacement of nutrients (FAO and ITPS, 2015) (See Figure 3.3b). Studies in the Russian Federation and Ukraine show that the loss of soil vegetation cover favours erosion processes, and soil organic matter content (SOM) can decline by 15, 25, and 40 percent in weak, medium, and severely eroded black soils (Iutynskaya and Patyka, 2010).

Using a quantitative global SOM-crop yield potential model, Oldfield, Bradford and Wood (2019) found

that wheat and maize yields are greater with higher concentrations of SOC and level off at approximately 2 percent SOC. Potential yield increases through higher SOC concentrations amount to 32 percent of the projected yield gap for maize and 60 percent of that for wheat.

The Status of the World's Soil Resources report (FAO and ITPS, 2015) concluded that a priority action should be to stabilize or increase the global SOM stocks (SOC and soil organisms). Locally appropriate SOC-improving management practices should be identified by each country and facilitate their implementation towards a national-level goal of achieving a stable or positive net SOC balance. Black soils should be prioritized to maintain and increase SOC stocks.

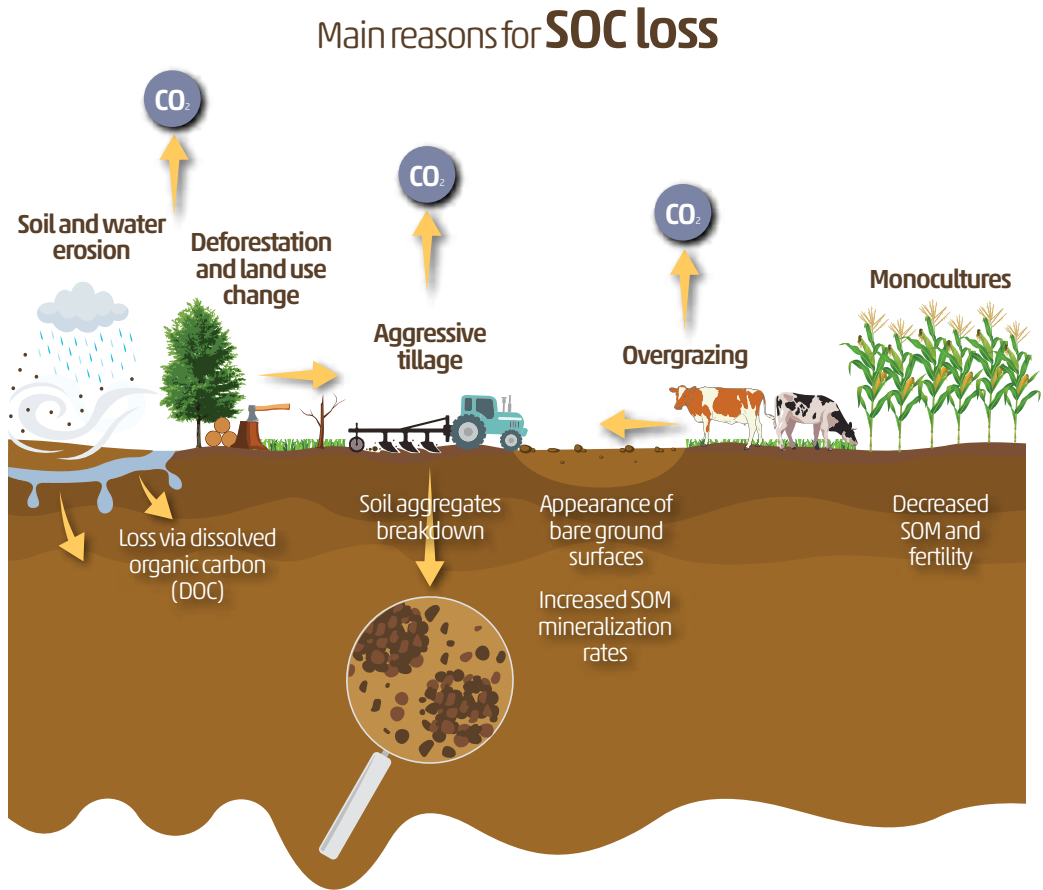


Figure 3.3b Mayor drivers of SOC loss
 Source: Author's elaboration

15 | Recarbonization of global soils (RECSOIL)



RECSOIL is a FAO innovative initiative with the aim to boost soil health through the maintenance and enhancement of SOC stocks (FAO and ITPS, 2021). It unlocks the potential of SOC to provide multiple benefits through key ecosystem services. Healthy soils directly contribute to enhance food security and farm income, reducing poverty and malnutrition, providing essential ecosystem services, contribute to the achievement of the SDGs, fight climate change, and build soils' resilience to extreme climatic events and to pandemics. Black soils are the most productive carbon-rich soils and contain 8.2 percent of the world's SOC stocks. Their SOC sequestration potential is 10 percent of the global annual potential (FAO, 2022). However, this is not evenly distributed throughout the world. For example, in Europe and Eurasia, black soils account for 66 percent of the potential SOC sequestration, while only reaching 10 percent in Latin America and the Caribbean. Therefore, it is critical to prioritize those areas to restore and maintain SOC stock and avoid losses. That can be done through the implementation of initiatives such as RECSOIL at country level to unlock the potential of these precious soils for climate changes adaptation and mitigation, and halt greenhouse gases emissions.

3.3.2 Soil erosion

Globally soil erosion was identified as the most severe threat, leading to poorer water quality in developed regions and to lower crop yields in many developing regions (Montanarella *et al.*, 2016). Figure 3.3a shows that soil erosion is the first main threat in regions where black soils are predominant or co-dominant, for example, South and North America, eastern Europe and northeast China.

Erosion induced by rainfall and wind degrades the quality of all soils, including black soils (See Figure

3.3.2). Due to the degree of severity that has occurred (such as deep gullies, total soil loss), many studies have been carried out during the last decade in the black soil region. The dominant soil erosion processes are due to water, wind, and snow meltwater, with water erosion on hillside farmland being the major contributor to soil erosion (Xu *et al.*, 2010). Ouyang *et al.*, (2018) observed that from 1979 to 2014, cropping system conversion from forestry to dry lands increased erosion losses from 204 to 421 tonnes per km² per year (Ouyang *et al.*, 2018). These losses can be controlled by basin, contour, rat tunnel, and conservation tillage,



© Wei Wan

in combination with terraces and strip cultivation. Crop productivity can be increased by fertilizer or manure application (Liu *et al.*, 2011).

In Japan, Taniyama (1990) reported that there was about 40 to 50 cm of topsoil loss by water erosion during the 16 years after land use change from forest to vegetable plantation in the Andosols of the northern Kanto region, Japan. Counter measures for soil erosion adopted in Japan include contour farming, cover cropping to prevent bare land, greenbelt farming, terracing. The Ministry of Agriculture, Forestry and Fishery (MAFF) in Japan has announced basic principles of soil water erosion and sediment control, namely enhancement of rain water percolation to reduce surface flow water, minimization of surface flow velocity, construction of channel networks to drain rain water rain water safely and decreasing soil erodibility.

More than 90 percent of the agricultural area of the Pampas region in Argentina is currently cultivated under no-till, more recently combined with the cultivation of “cover crops” during the fallow period. This tends to reduce the loss of organic carbon and soil erosion due to the generalization of no-till practices.

Wind erosion is a phenomenon that mainly affects soils in semi-arid and arid areas, which often have low levels

of plant cover and organic matter (Skidmore, 2017). In any case, climatic cycles with drought can generate predisposing causes of wind erosion, even in black soils, as happened with the dust bowl during the 1930s in the United States of America (Lee and Gill, 2015).

The combined effect of water and wind in Ukraine has been severe. The average annual soil loss from water and wind erosion is 15 tonnes/ha. This means that the country’s soil cover loses about 740 million tonnes of the top, fertile soil layer every year (Baliuk *et al.*, 2010). The amount of land in Ukraine damaged by water erosion is up to 32 percent of the total area (13.3 million hectares). Of these hectares, 4.5 million hectares with medium and heavily washed soils, as well as 68 000 hectares that have completely lost the humus horizon. More than 6 million hectares are systematically affected by wind erosion, and up to 20 million hectares in years with dust storms. A particularly potentially dangerous zone in Ukraine is the southern Steppe (the main zone with Kastanozems and Calcic Glosic Chernozems). Thus, the number of days per year with dust storms in the southern steppe zone is 159, northern and central is 88, Forest-Steppe is about 33 days (Baliuk *et al.*, 2010).

Land use change

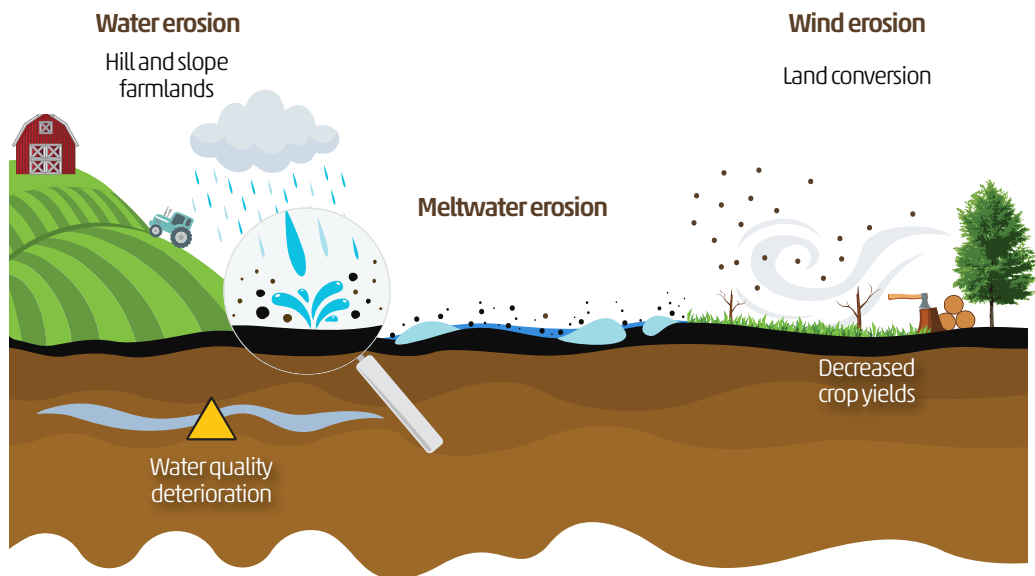


Figure 3.3.2 Main soil erosion processes of black soils

Source: Author's elaboration



© Andrei Borisovich Razanov

Photo 3.3.2a Wind erosion in Liaoning province, China



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Photo 3.3.2b Water erosion in Laetoli Gorge, the United Republic of Tanzania



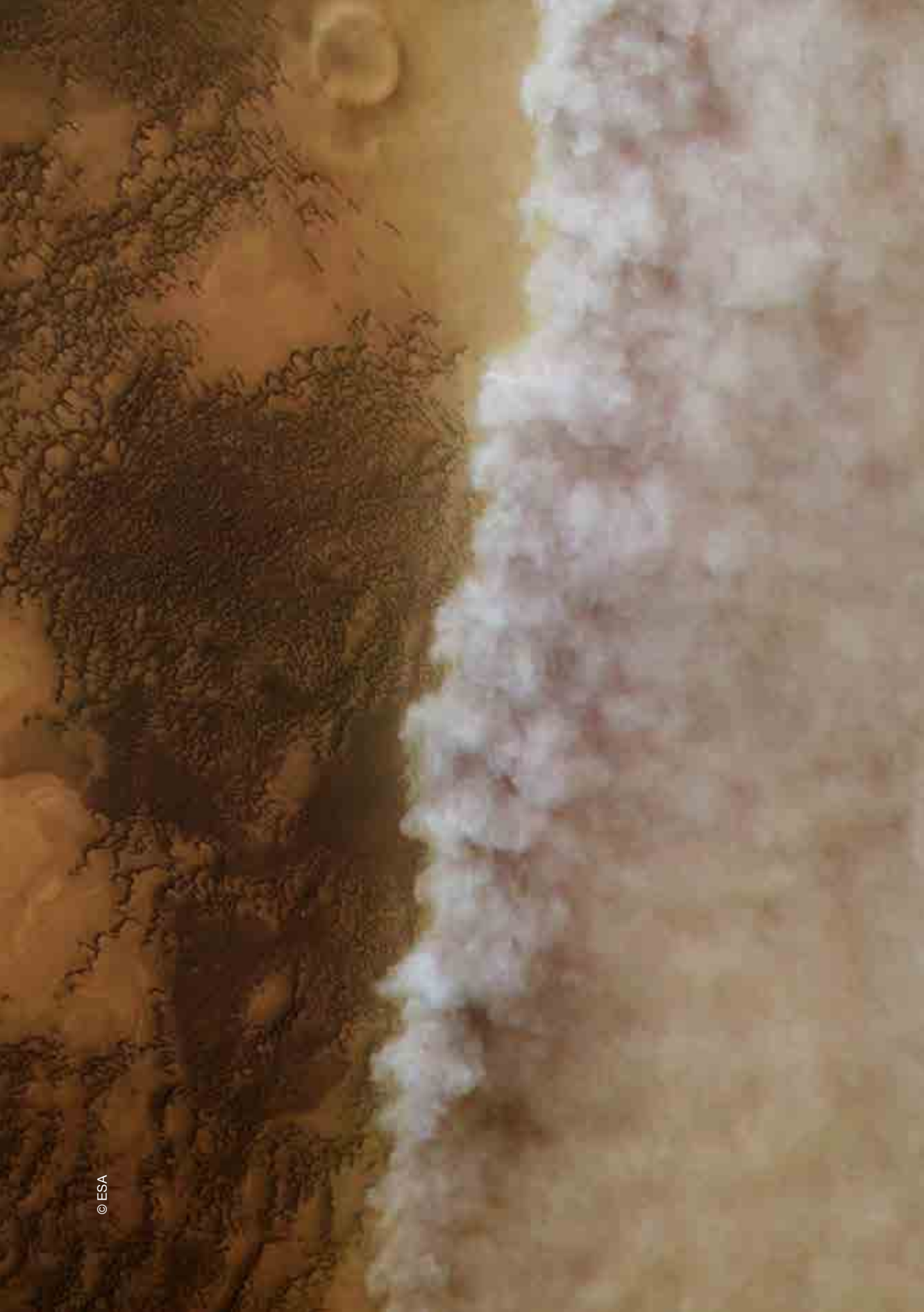
© Irina Kalimova

Photo 3.3.2c Wind erosion in Jiusan farm, China caused by land conversion and aggressive tillage



© Irina Kalimova

Photo 3.3.2d Water erosion in the Russian Federation



16 | The infamous Dust Bowl!



Dust storm approaching Stratford, Texas. Dust Bowl surveying in Texas.

The Dust Bowl was one of the largest sandstorms in the history of the United States of America that happened in the 1930s (History, 2020). This phenomenon began in the southern Great Plains and was caused by intensive farming, poor agricultural practices, and was associated with a period of severe droughts (History, 2020). Soil erosion and desertification on these lands caused massive dust storms affecting the states of Oklahoma, Kansas, Texas, New Mexico, and Colorado (Texas and Kansas have black soils) and reaching cities such as Washington, DC, and New York (Findmypast, 2015; SSSA, 2015). About 1.2 billion tonnes of soil were lost between 1934 and 1935 in the southern Great Plains (Britannica, 2022). These dust storms caused several adverse effects such as respiratory diseases causing the death of people and animals, with farmlands becoming unusable, and hunger and poverty spreading across several states (SSSA, 2015). Many people migrated to other places like California to escape the drought and the dust, and to find work (Findmypast, 2015). Following this huge catastrophe, the Soil Conservation Service (later the USDA Natural Resources Conservation Service) was founded to encourage farmers to adopt erosion mitigation strategies implementing sustainable management practices (reduced tillage, leaving crop residues in fields, strip cropping and crop rotation) to conserve soil and minimize erosion (SSSA, 2015). Desertification increasingly threatens significant land areas worldwide, affecting more than 100 countries, including the United States of America (SSSA, 2015).

Source: History, 2020. *Dust Bowl*. In: HISTORY. Cited 6 June 2022. <https://www.history.com/topics/great-depression/dust-bowl>

3.3.3 Soil nutrient imbalance

Nutrient imbalances include both deficits and excesses of soil nutrients. Imbalances were judged by Montanarella *et al.*, (2016) as the second main threat in North America, and the third greatest threat in most of Africa, in regions where black soils are conspicuous (See Figure 3.3.3).

Nitrogen (N) and phosphorus (P) fertilizer use need to be increased in infertile tropical and semi-tropical soils where the most food insecurity is found. Soil nutrient levels have decreased in the Argentine Pampas, because of the lack of resupply of nutrients, causing soil fertility to be exhausted in many places. Due to economic reasons, fertilizer use and soil testing was not historically widespread in Argentina and the level of nutrients such as N, P, calcium (Ca), magnesium (Mg) and zinc (Zn) has decreased (Rubio *et al.*, 2019; Lavado and Taboada, 2009). Nutrient stocks have also noticeably decreased in black soils of the Russian Federation (Grekov *et al.*, 2011; Medvedev, 2012), Ukraine (Balyuk and Medvedev, 2012), and Brazil (Rezapour and Alipour, 2017).

On the other hand, in other parts of the world with black soils, excessive N fertilization and decreasing N recovery rates by crops have caused dramatic increases in non-point source pollution from agriculture (Ju *et al.*, 2004). Nutrient excesses often originate in the use of high doses of synthetic fertilizers and organic

manures containing N and P, with the consequent risks of pollution and therefore the eutrophication of groundwater and surface water (See Figure 3.3.3).

Soil phosphorus is strongly affected by interaction with soil minerals and organic matter. Due to this, P added as fertilizer (14.2 Tg P/year) and manure (9.6 Tg P/year) collectively exceeded P removal by harvested crops (12.3 Tg of P/year) at the global scale (Zang *et al.*, 2017). However, almost 30 percent of the global cropland area, particularly in Europe and South America, is deficient in soil P, either total or extractable by crops. Soil P deficits are common in areas producing forage crops used as livestock feed (MacDonald *et al.*, 2011). On the other hand, high P fertilizer application relative to crop P use resulted in a greater proportion of intense P surpluses (>13 kg of P/ha/year) in many areas with black soils. Together with N excesses, P surpluses represent a risk of eutrophication of freshwater and marine ecosystems (Dodds and Smith, 2016; Ngatia *et al.*, 2019). In Japan the overuse of chemical fertilizer causes nutrient imbalance in Andosols. Potassium is excessively accumulated in upland soils, and the ratio of magnesium to potassium is low (Japanese Soil Conservation Research Project Nationwide Council, 2021). The level of available phosphate in upland soils tends to be higher than the governmental recommendation (Japanese Soil Conservation Research Project Nationwide Council, 2021).



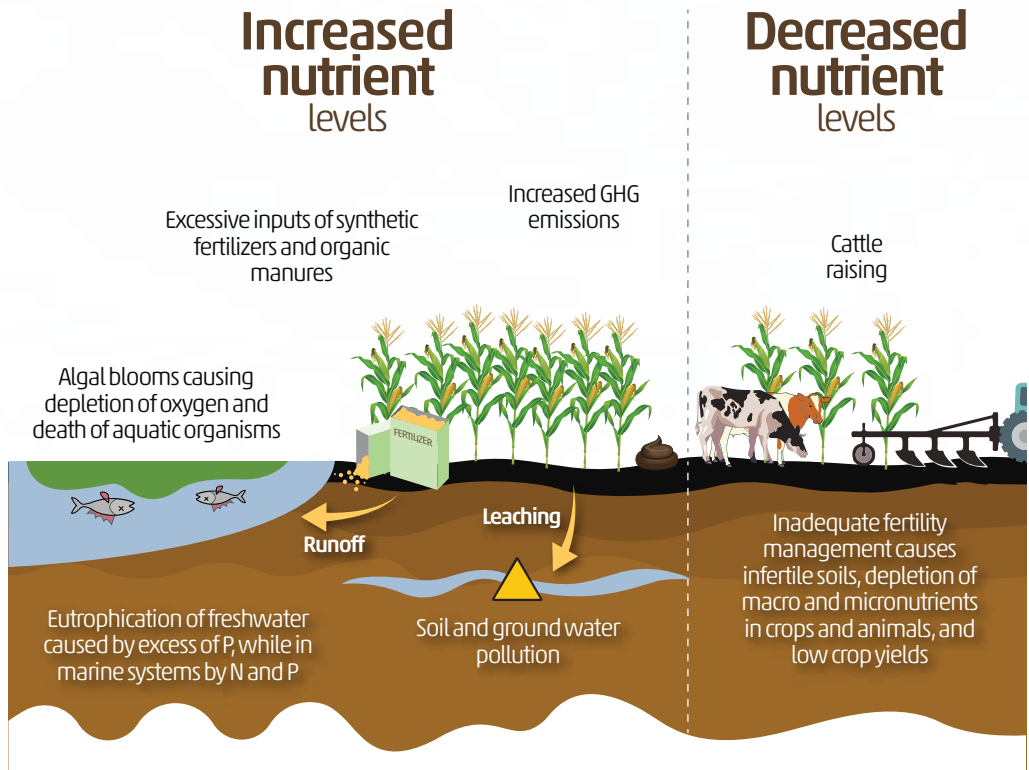


Figure 3.3.3 Effects of intensive use as a trigger on nutrient imbalance

Source: Author's elaboration



3.3.4 Soil compaction

Excessive soil compaction is a direct consequence of intense agricultural traffic of heavy machinery in the fields (See Figure 3.3.4), and a higher soil susceptibility because of organic matter content decreases and lower aggregate stability (Gupta and Allmaras, 1987; Montanarella *et al.*, 2016). Soil compaction is indicated by increases in soil bulk density and soil penetrometer resistance and decreases in soil macroporosity and water infiltration rates, among changes in other soil properties (Gupta and Allmaras, 1987; Liu *et al.*, 2010), with important consequences on crop yields (Liu *et al.*, 2010; Peralta, Alvarez and Taboada, 2021). Evidence of soil compaction and physical deterioration of black soils is widely available. After 75 years of cultivation, water-stable aggregation declined by 27 percent and clay content by 27 percent in black soils of the Russian Federation (Balashov and Buchkina, 2011). This soil physical decline reached 40 percent in Ukraine, where many soils have a compacted layer (Balyuk and Medvedev, 2012). Likewise, intensive cultivation and summer fallowing have degraded the Canadian prairie soils, resulting in poor surface structure (Agriculture and Agri-Food Canada, 2003). Without significant variation, 14 to 20 percent higher bulk density and 10 to 22 percent lower porosity values were observed in cultivated black soils compared to forestlands in Brazil (Rezapour and Alipour, 2017).

Soil physical degradation has covered almost the entire area of distribution of black soils in Ukraine. This is due to a number of factors, including excessive ploughing of agricultural land (78 percent) (Medvedev, 2012; Yatsuk, 2015; Yatsuk, 2018; National report on the state of the environment in Ukraine in 2018, 2020), due to their suboptimal structure, intensive mechanical tillage led to widespread physical degradation. Physical degradation is manifested in the destructing of the upper layer, blocky (cloddy) after ploughing, swimming

and crusting, the presence of a plough pan, and subsoil compaction. Physically degraded soils are prone to erosion, poor water retention properties, thus limiting the development of plant root systems (Baliuk *et al.*, 2010; Medvedev, 2012). In addition, with the current trends of climate change (aridization and warming) in Ukraine, there is already a de facto shift of natural-climatic zones from 100 to 150 km to the north, which brings new threats to desertification (Zatula and Zatula, 2020). These processes were already clearly traced 20 years ago (Pylypenko *et al.*, 2002).

Soil compaction is not only a consequence of tillage, as even under continuous conservation tillage farming it was repeatedly observed (Peralta, Alvarez and Taboada, 2021). In this case, the process affects the first layer of the soil, promotes planar aggregates and associated voids in crop rotations with long fallow periods (Alvarez *et al.*, 2014; Peralta, Alvarez and Taboada, 2021).

Additionally, burning, intensive grazing, tilling, and replacement of the natural grassland with more nutritive grass species in Colombia significantly affected water balance of the Colombian moorlands areas (Sarmiento and Frolich, 2002). Phenomena typically accompanying pasture farming and tillage, such as soil compaction and soil crusting, additionally alter the infiltration rates, water storage, and regulation capacity of moorlands.

The soils of the Pampas region in Argentine provide an example of the consequences of physical soil degradation. Continuous cultivation has generated soil physical degradation as sealing and compaction, increasing the processes of water erosion. Since the soils of the Pampas region, particularly in the Undulating Pampa, have been put into cultivation, they have lost an average of 50 percent of their original organic matter, while the total phosphorus of the surface horizon would have decreased by 80 percent (Sainz-Rozas, Echeverria and Angelini, 2011; Lavado, 2016).



Good soil structure vs. compacted soil

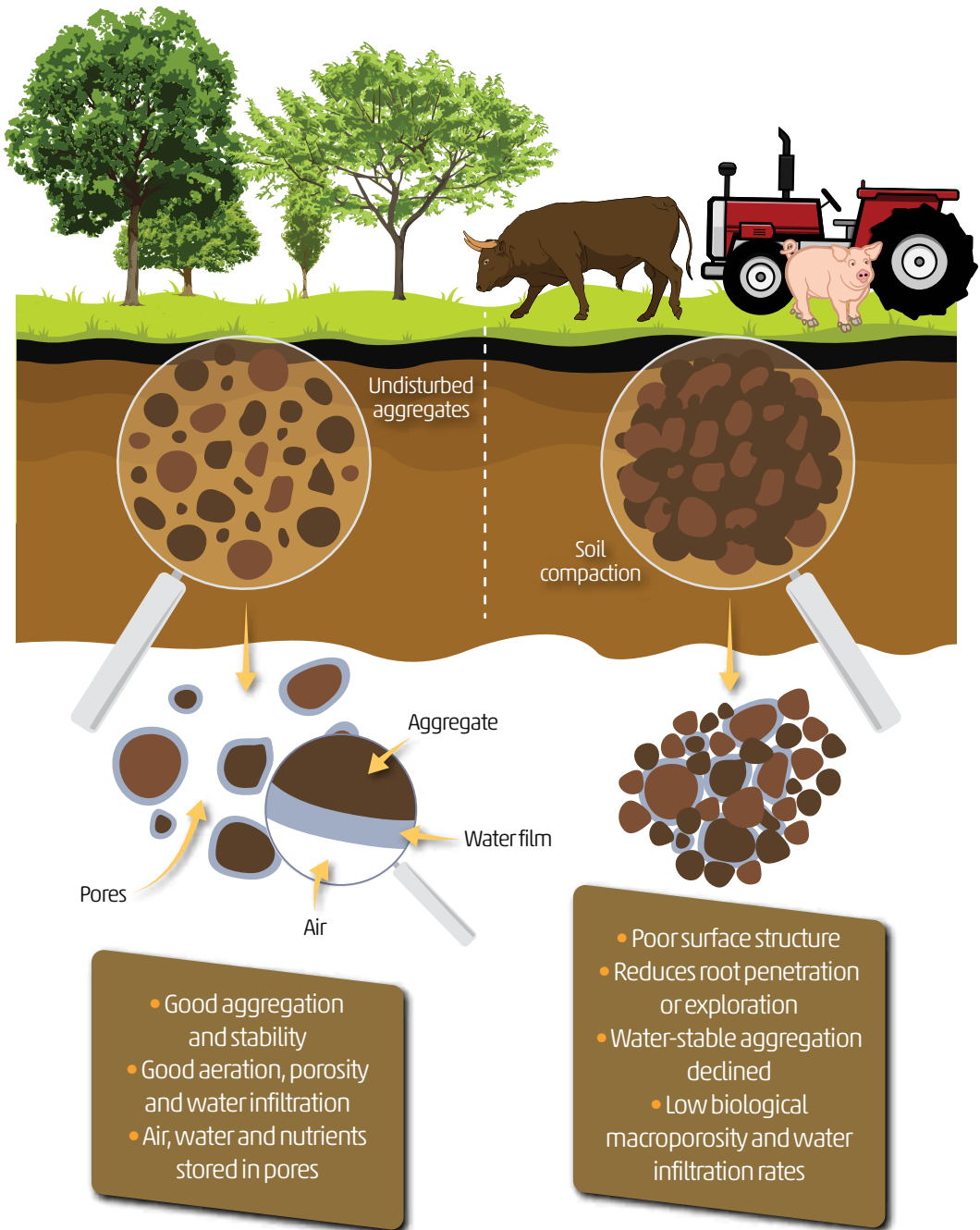


Figure 3.3.4 Effects of soil compaction

Source: Author's elaboration



Photo 3.3.4a Soil compaction caused by heavy machinery in Jilin province, China



Photo 3.3.4b Soil compaction caused by heavy machinery in Jilin province, China

3.3.5 Salinization

Salinization is a related processes that result from both natural (primary) and human-induced (secondary) processes (See Figure 3.3.5). In black soils the cases are due to: a) hydrological imbalances caused by changes in land use (such as the replacement of perennial vegetation such as forests, grasslands and pastures by annual crops), or associated with climate change, which causes the rise of saline groundwater to the surface (Taboada *et al.*, 2021); or b) the use of irrigation water with moderate to high salt content (Choudhary and Kharche, 2018; Bilanchyn *et al.*,

2021). In both cases, the increases in pH, electrical conductivity, and percentage of exchangeable sodium, decrease the quality of black soils. However, human-induced salinization owing to inappropriate soil and fertilizer management are the main challenges in regions of black soils. Secondary salinization of irrigated soils, accompanied by a reduction of the humus-rich layer depth was reported in the Russian Federation (Grekov *et al.*, 2011; Medvedev, 2012). In other cases, soil salinity in black soils is associated with swelling-shrinking processes and is not shown by salt pans on surface (Choudhary and Kharche, 2018).

Soils affected by human-induced salinity

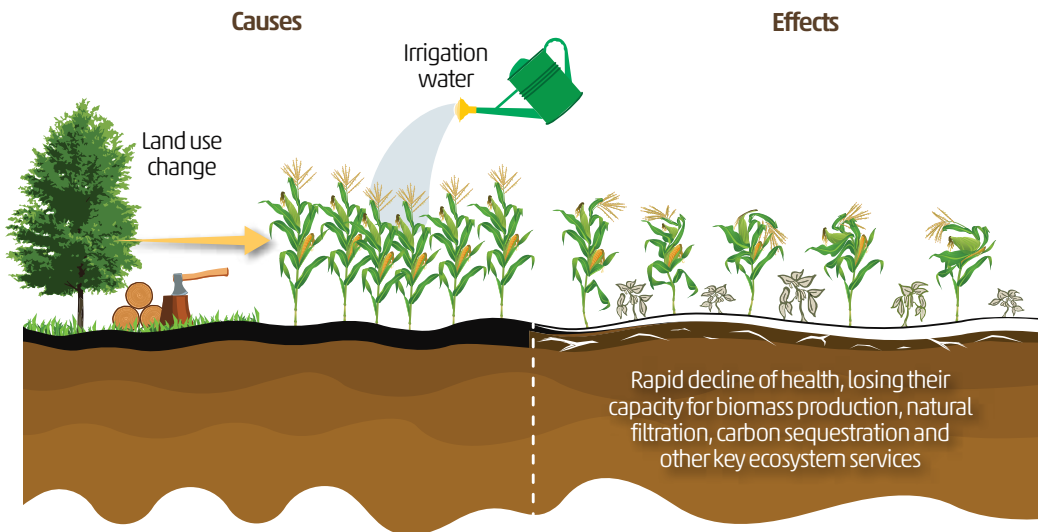


Figure 3.3.5 Soils affected by human-induced salinity

Source: Author's elaboration



3.3.6 Acidification

The acidification of black soils is most commonly due to an excessive extraction of exchangeable bases (Ca, Mg, K) by crops without adequate replenishment or a consequence of N fertilization (See Figure 3.3.6). Acidification only appears as the first main threat in Oceania (See Figure 3.3a). In the regions of Cherkassy and Sumy (Ukraine), soil pH dropped 0.3 to 0.5 units after 40 to 50 years cultivation (Grekov *et al.*, 2011; Medvedev, 2012). In black soils of northeast China, from 2005 to 2014, a trend of acidification due to overuse of N fertilizers was detected in intensive cropping systems (Tong, 2018). It is interesting to note that in Chinese croplands, N-induced acidification was also associated with an accrual of soil organic matter (Zhang and Liu, 2020), and a great decrease in soil inorganic carbon (Raza *et al.*, 2020). Andosols in Japan can experience nutrient issues associated with acidification. In general, allophanic

Silandic Andosols are originally weakly acidic, and aluminum toxicity does not occur frequently in plants on these soils. However, Silandic Andosols can become strongly acidic following the heavy application of chemical fertilizer (Fujii, Mori and Matsumoto, 2021). Strongly acidic Andosols with an accumulation of acidic materials dissolves a part of the active Al fraction in the soils, which causes Al toxicity and thereby leads to the shallow rooting of Al-susceptible crops (Fujii, Mori and Matsumoto, 2021). Additionally, the soil productivity of strongly acidic Andosols is lower than that of the original weakly acidic soil; for example, the number of bacteria decreases (e.g, from 160×10^6 cfu /g for weakly acidic soil to 10×10^6 cfu /g for strongly acidic soil) as do the levels of readily mineralizable soil nitrogen (Matsuyama *et al.*, 2005). To improve these nutritional imbalances, the appropriate use of soil amendments based on soil diagnosis is desired (Japanese Soil Conservation Research Project Nationwide Council, 2021).



Soil acidification

Causes

- Anthropic
 - Excessive inputs of nitrogen (as NH_4^+)
 - Legume monoculture
 - Acid rain
 - Removal of all harvested materials and no reposition of exchangeable bases
- Natural
 - High rainfall and weathering oxidation

Effects

- pH drop (< 5.5)
- Leaching of nitrates (NO_3^-)
- Soil pollution
- Toxicity: Al^{3+} , H^+ , Fe and Mn sesquioxides
- Deficiency: P, Ca^{2+} , Mo, Mg^{2+}

Soil pH chart

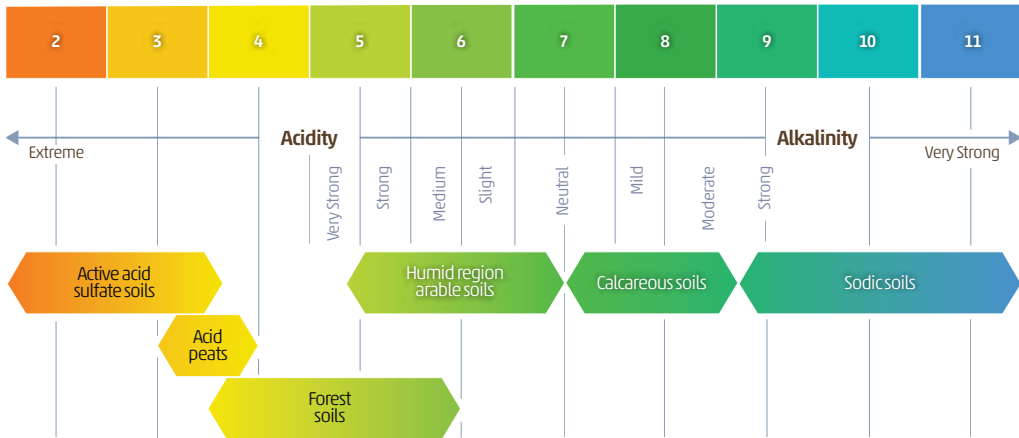


Figure 3.3.6 Causes and effects of soil acidification

Source: Author's elaboration

3.3.7 Soil biodiversity loss

Unlike other aspects of soil science, soil biodiversity remains poorly understood, in terms of anthropogenic impacts on the diversity of microbes and soil fauna that live unseen in soils. Only a small fraction of the immense morphological diversity of soil organisms is

known, and this is especially true for microorganisms. Examples of this biological richness include bacteria (a), microscopic (b) and fruiting bodies of fungi (c), viruses (d), algae (e), protists (f), nematodes (g), mites (h), springtails (i), enchytraeids (j), earthworms (k), mealybugs (l), termites (m), ants (n), and mammals (o), among many others (Figure 3. 3.7a).



Figure 3.3.7a Overview of the most common soil biodiversity groups

Examples shown are bacteria (A), microscopic (B) and fruiting bodies of fungi (C), viruses (D), algae (E), protists (F), nematodes (G), mites (H), springtails (I), enchytraeids (J), earthworms (k), mealybugs (L), termites (M), ants (N), and mammals (O), among many others

Source: Author's elaboration

Most of black soils evolved supporting grassland vegetation with an active rhizosphere around the fibrous root system of the dominant grasses (Tisdall and Oades, 1982; Oades, 1993). These grasslands were characterized by floristic richness in plant communities, and an enormous soil biodiversity (from microbes to megafauna) which plays a key role in the provision of essential ecosystem services as carbon sequestration, nutrient cycling (carbon, nitrogen, phosphorus, and sulphur), water retention, provision of nutritious food, among others.

One of the consequences of the transition to crops from grasslands on black soils is the loss of much of the original biodiversity, at levels that are not well known because these changes occurred a long time ago. It is difficult to think that these soils will recover their pristine or near pristine state, so one of the future challenges is how to recover at least part of this enormous lost biodiversity.

The effects of reducing soil biodiversity on soil functioning was studied in an experiment by Wagg *et al.*, (2014). A broad soil biodiversity gradient was reproduced in grassland microcosms (Figure 3.3.7b). Some groups of soil organisms (nematodes and mycorrhizal fungi) were eliminated within the gradient, while fungal and bacterial communities reduced in abundance and richness. Plant species diversity decreased strongly with the reduction of soil biodiversity and the simplification of soil communities. This supports previous findings that plant community composition is driven by the diversity and species composition of various groups of soil organisms. As is expected (and repeatedly seen in real examples), carbon sequestration also decreased along the gradient. Changes in soil biodiversity and soil community composition also influenced processes related to nutrient cycling.

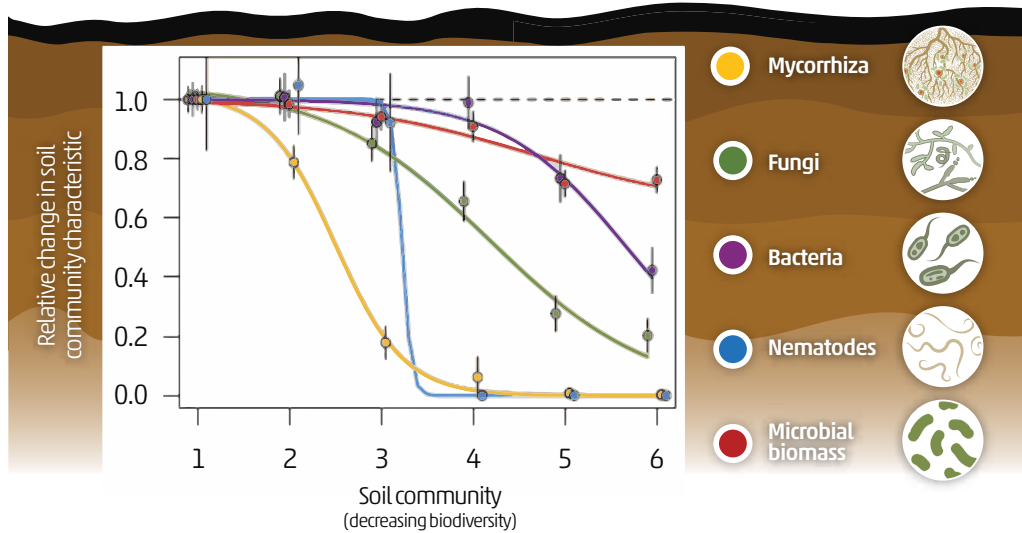


Figure 3.3.7b Change in soil community characteristics (abundance and richness) of various guilds of soil organisms in grassland communities

Means \pm SEM are expressed as a ratio of the most complete soil treatment (dashed line), such that 0 represents no detection. The coloured lines highlight the general trend of changes in soil community characteristics along the gradient.

Source: Wagg, C., Bender, S.F., Widmer, F. & Van Der Heijden, M.G. 2014. Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proceedings of the National Academy of Sciences*, 111(14): 5266–5270. <https://doi.org/10.1073/pnas.1320054111>

This simplification of soil communities due to cultivation has also been observed in the field. A valuable example of changes in arthropod communities (spiders, ants and carabids, among others) is provided by a study on black soils in northern China (Gao *et al.*, 2021). Due to intensive agricultural practices, a more simplified species richness and biodiversity was achieved at the local scale.

A well-documented effect of soil organisms is on the aggregation of the soil. The structure of the topsoil of black soils presents a hierarchical organization of aggregate sizes that depends on this enormous

biodiversity. In fact, soil macroaggregates and soil clumps (units > 250 microns) depend for their stability on the binding and bonding mechanisms from cementing agents excreted in the soil rhizosphere and entanglement by fine roots and mycorrhizal hyphae. Soil mesopores (0.2 to 30 microns in diameter) and macropores (larger than 30 microns) are the habitat of many of the microorganisms and microfauna that make up soil biodiversity (Degens, 1997; Kay, 1990; Chantigny *et al.*, 1997). The protection of SOC within aggregates is a key element of increasing SOC levels to achieve carbon sequestration.



17 | What is the relationship between wars and soil pollution?

The use of artillery possesses a severe risk to soil degradation and pollution especially with the use of mechanization and modern weapon technologies. The most common sources of pollution affected by armed conflicts are the following contaminants:

Sources of pollution	Soil contaminants
Conventional explosives	TNT, RDX, HMX
Fragmentation shells, bullets, cartridge cases and shotgun pellets	Copper, iron, lead and zinc
Armour-piercing projectiles	Depleted uranium
Incendiary weapons	White phosphorus and Napalm

Soil pollution can come from the use of nitro aromatic explosive compounds (FAO and UNEP, 2021). These compounds have a high persistence and once entered the soil, they tend to remain, harming the local biota and reducing the soil health and fertility. The negative effects from the use of incendiary weapons containing white phosphorus comes from their co-contaminants and residues of combustion. Such weapons may result in soil polluted with trace elements, hydrocarbons, organic solvents, surfactants, synthetic phenols, cyanide, dioxins, and radionuclides reducing soil fertility, crop yield and possessing risk to human health and the environment. The use of depleted uranium, one of the least studied forms of uranium, can penetrate the soil as deep as 50 cm. The dust that is emitted from the depleted uranium disperses and contaminates and polluting the soil over large area. Claims have been made that the depleted uranium dust can travel up to 40 km. After an attack with depleted uranium ammunition, this dust will be deposited on the ground and other surfaces as partially oxidized depleted uranium fragments of different sizes, and as uranium oxide dust.

The sources of soil pollution are very varied and range from the primary sector to the final stages of the life cycle of everyday products. For this reason, in order to prevent and reduce soil pollution by the armed conflicts, greater efforts must be made to reduce the use and production of toxic chemicals in the ammunition, to regulate and control industries and verify that their emissions do not introduce contaminants into the environment and that production and consumption systems move towards more sustainable schemes in which waste production is reduced.

Source: FAO & UNEP, 2021. *Global assessment of soil pollution – Summary for policy makers*. Rome, FAO. <https://doi.org/10.4060/cb4827en>

3.4 Challenges

The challenges faced by black soils arise from their preponderant role in food and fibre production under agricultural and livestock use. As mentioned before, the main threats that operate on them are erosion by water, tillage and wind, loss of SOC and organic matter, and nutrient imbalance. In addition, physical-structural deterioration should not be ruled out, and in some regions soil salinization, pollution with excess fertilizers and agrochemicals, and soil sealing due to urban advancement also occurs (FAO and ITPS

2015; Montanarella *et al.*, 2016). Main drivers of soil degradation are land use changes and unsuitable land management, unsustainable management practices and the lack of policies.

According to the FAO and ITPS, (2015) report, soil degradation should be minimized and degraded soils restored in those regions where people are most vulnerable, or where food production is critical, Global SOC and SOM stocks should be stabilized or increased, and that we should act to stabilize or reduce global N and P fertilizer use while simultaneously increasing fertilizer use in regions of nutrient deficiency.



Photo 3.3.7 Black soils in Zhaoguang farm of Heilongjiang province, China

3.4.1 Land use change and land management

Due to projected increases in food demand crop production will need to increase by 70 to 110 percent by 2050 (Royal Society of London, 2009; Tilman *et al.*, 2011). As very fertile soils, black soils will be among the main actors in these increases in production and closing of gaps. To meet this objective, sustainable intensification of the current productive systems rather than agricultural expansion into forests and pastures is critical (Fischer and Connor, 2018; Guilpart *et al.*, 2017). Many black soils are also considered soils of high environmental value, where the protection of large carbon stocks and the restoration of these stocks should be included in overall soil resilience programmes to monitor, restore and maintain soil fertility and soil functions, and to enhance the key ecosystem services provided by these soils (Smith *et al.*, 2016).

As a successful example, in recent years, the Ministries of Agriculture, Science and Technology, Land and Resources, and the four provinces of black soil areas in northeast China have actively implemented a wide range of measures to protect and enhance black soils. These include high standard farmland construction, soil and water conservation, soil testing and formulated fertilization, soil organic matter increases, conservation tillage (reduced tillage and no-till), subsoiling for soil compaction alleviation and soil preparation, straw returning, and increasing the use of organic fertilizers (Li *et al.*, 2021). The comprehensive goal of black soil protection and utilization is to control the loss and degradation of black soils and keep water and fertility (Han *et al.*, 2018).

The adoption of restorative land use and recommended management practices are key to strengthen numerous ecosystem services provided by black soils, such as improving water quality and renewability, increasing below and above-ground biodiversity, enhancing soil resilience to climate change and extreme events, and mitigating climate change by sequestering carbon in soil and reducing CO₂, CH₄ and N₂O emissions (Lal, 2014).

3.4.2 Unsustainable management practices

The most cited unsustainable management practices for black soils are those that cause the main threats, that is, erosion, loss of SOC and SOM, nutrient imbalance, and salinization and sodification. Under agricultural management, these practices are usually aggressive

tillage methods based on plowshares and disc plows, harrows, and so on, monocultures, non-replenishment of nutrients with fertilizers, and the disappearance of pastures. Overgrazing and non-use of rational grazing systems is the most frequent cause on land destined for grazing. Soil pollution by pesticide residues is a major cause of degradation (Smith *et al.*, 2016).

3.4.3 Climate change and black soils

Climate change is very much related to the condition of black soils. From one side, climate change negatively impacts black soils. For instance, interactions between the increasing temperature and decreasing precipitation in black soil region led to reduced accumulation of soil organic matter, which results in poor soil fertility (Gong *et al.*, 2013). On the other side, the unsustainable management of black soils causes the loss of soil organic carbon and emits greenhouse gases to the atmosphere, exacerbating climate change. Evidence in black soils showed that organic matter amendments and tillage management can mitigate negative and exploit positive effects of climate change on crop production by enhancing soil quality (Song *et al.*, 2015; Menšík *et al.*, 2019; Farkas, *et al.*, 2018). Unfortunately, those practices are not often adopted by local governments and farmers due to multiple management and economic obstacles. The restoration of degraded black soils should be highlighted and inputted in the global climate change agenda in offsetting anthropogenic emissions and SOC sequestration (Lal, 2021).

3.4.4 Lack of policies

Many of the black soils appear in countries with low levels of soil governance, or where different laws and regulations relating to soil and water may exist, but with poor enforcement. Undoubtedly, the lack of effective policies in these sites is a major challenge to preserve the quality and health of black soils for agricultural use, and thus food security.

The implementation of practices for recovery or restoration of black soils mostly depends on good governance (in North America) and the availability of financial resources. This factor limits implementation of sustainable practices in all the affected countries, but mostly in developed countries. The problem lies in the fact that most of the food insecurity problems are not in the more developed countries but in the less developed parts of the world. This is the main challenge for sustainable management, not only for black soils, but also for all the productive soils in the world. Sustainable soil management should increase the supply of healthy food.





4. Sustainable management of black soils: from practices to policies

4.1 Good practices to address sustainable management of black soils

In the coming decades, a crucial challenge for humanity will be meeting future food demands without further undermining the integrity of the Earth's environmental systems. As the food basket of the world, black soils are already degraded significantly after land use change from natural ecosystem to farmland, but main soil threats such as erosion by water and wind, loss of soil organic carbon (SOC) and soil organic matter (SOM), and nutrient imbalance will further endanger its ecosystem service functions. For example, during the past several decades, black soils have lost about 50 percent of their initial SOC stock due to soil erosion, degradation, and other unsustainable human activities (Gollany *et al.*, 2011). Responding to these threats, there is increasing focus on 'Sustainable Soil Management' as a means to maintain or increase productivity on underperforming black soils while simultaneously decreasing the environmental impacts of management practices. However, it is unclear what such efforts might entail for the future of intergraded management practices and policy strategies for black soil conservation. Here we present a global scale assessment of sustainable management practices of black soils that may be necessary to achieve increased yields and decreased environmental impact.

18 | Sinograin II: Technological innovation to support environmentally – friendly food production and food safety under a changing climate – opportunities and challenges for Norway–China cooperation



Black soil project implementation, Harbin China, May 2022.

The Sinograin II project, a collaborative project between Norway and China, aims to exploit smart agricultural technologies to improve the sustainability of agriculture in China. Black soils in the north-eastern region of China are very fertile and are mainly used for grain production (Dybdal 2019, 2020), and have been described as a “giant panda in cultivated land”. However, the intensive agricultural production, the lack of sustainable soil management practices and the excessive use of fertilizers have led to a decline in their fertility. With the aim of restoring these soils and implementing climate-smart agrotechnologies such as precision fertilization and APP-based tools for sustainable production systems, scientists from the Norwegian Institute of Bioeconomy Research (NIBIO), the Chinese Academy of Agricultural Sciences (CAAS), Heilongjiang Academy of Agricultural Sciences (HAAS), Nanjing Agricultural University and other Chinese partners are collaborating on the Sinograin II project. This project, which is financed by the Norwegian Ministry of Foreign Affairs, and a total budget of NOK 18.8 million, seeks to apply innovative technologies that contribute to food security and the environment in China. Sinograin II is mainly based on precision nitrogen management technologies, automatic pest prediction to improve pesticide use efficiency, influence of innovative farming technologies, management of nutrient inputs for sustainable food production, and research on the agro-tech extension and household adoption of precision agricultural technology and its economic, social and environmental effects. One technology being developed for black soils in the Heilongjiang region is the validation of a digital soil health card (SHC). This card is easy for farmers to use and makes use of soil health information such as soil structure and number of earthworms in the soil, among other parameters. Using this card allows farmers to make decisions on nutrient and fertilizer requirements for individual farms in order to improve the productivity of their crops while maintaining healthy soils. An APP-based SHC is under development and shall be tested in the near future. The development and exploitation of these climate-smart tools promotes and contributes to the protection, restoration and sustainable management of black soils.

4.1.1 Tillage

To reduce the impact of tillage and seeding systems on soil health, the frequency (number of passes across the field that results in a soil disturbance) and intensity (mass of soil disturbed in a single pass) must be reduced. Conventional tillage (CT) usually involves a complete inversion of the soil with a moldboard or disc-plough followed by several tillage operations before seeding. For example, CT which includes moldboard plough (MP), has caused the loss of SOC and the severe soil degradation of soil structure in black soil region due to its very fine-grained feature (Sun *et al.*, 2016). Much of the tillage research has focused on physical and chemical processes under contrasting tillage systems, and found that conservation tillage increased the soil

water content, soil macroporosity and soil organic carbon content and decreased soil bulk density. A range of tillage and seeding systems have been developed to reduce the intensity and frequency with the objective of maintaining and improving soil health and crop yield. Tillage and seeding systems for conservation management tend to fall into three categories, non-inversion tillage, strip tillage and no-till, with tillage intensity and frequency decreasing as you move from non-inversion tillage to strip tillage and finally to no-till (Morris *et al.*, 2010). It is also important to recognize that complementary agronomic practices need to be used in an integrated system with tillage and seeding management practices to protect and conserve black soils (Freitas and Landers, 2014; Veum *et al.*, 2015; Nunes *et al.*, 2018).



Non-inversion tillage

Description of the practice

Non-inversion tillage includes crop production systems which mix crop residues with the top 8 to 10 cm of soil in the entire row and inter row area (Hayes, 1985; Morris

et al., 2010). A protective quantity of residue is left on the soil surface during the year. The cultivator system, chisel system, disk system, stubble mulch system, rotary tillage system, and similar systems are all considered to be non-inversion tillage (Photo 4.1.1a).



Photo 4.1.1a Non-inversion tillage, Shirokiv of Ukraine

Range of applicability

The technique is applied under a wide variety of climate conditions and crops such as soybean and maize in black soil areas. It can be potentially applied to all climatic areas and crops, in climatic zones such as warm temperate dry, warm temperate humid, cool temperate moist, and tropical wet.

Benefits of the practice

Non-inversion tillage was found to improve many physical, chemical and biological soil properties compared to CT (Holland *et al.*, 2004). For instance, with monoculture maize in a black soil area in temperate zone of northeast China, non-inversion tillage reduced soil erosion compared to conventional tillage (Sun *et al.*, 2016). In addition, non-inversion tillage combined with maize-soybean rotation enhanced the soil microbial metabolic activity and increased the fungi-to-bacteria (F/B) ratio in the plough layer, and improved microbial biomass and abundance in the surface layer (Sun *et al.*, 2016). Amino sugar is also an essential tool for investigating the presence of microbial residues in soil, higher amino sugar content in CT improves long-term SOC stabilization in black soils more than traditionally believed (Sun *et al.*, 2016). These practices are

especially important in addressing soil erosion, SOC and biodiversity loss, and compaction.

Recommendations and potential barriers for adoption

Non-inversion tillage can reduce soil erosion compared to convention tillage, but if several tillage operations occur between cropping seasons with very little residue left on the soil surface, there is very little protection of the black soils that may lead to soil degradation.

No-till

Description of the practice

No-till is a system where a crop is planted directly into a seedbed that has not been tilled since harvest of the previous crop. It is a common practice used in black soil regions of the world. It is also called zero tillage, under the umbrella of conservation agriculture. The no-till operation consists of a one-pass planting and fertilizer operation in which the soil and the surface residues are minimally disturbed. No-till systems eliminate all mechanical seedbed preparation before seeding and fertilizer placement except for the opening of a narrow (2 to 3 cm wide) strip or small hole in the ground for seed placement to ensure adequate seed to soil contact. The entire soil surface is covered by crop residue,

mulch or sod. The surface residues of such a system are of critical importance for soil and water conservation. Weed control is generally achieved with herbicides

or in some cases with cover crops and crop rotation (Derpsch, 2003) (Photo 4.1.1b).



Photo 4.1.1b No-till maize crop, Pampas of Argentina

Range of applicability

On black soils, particularly in grasslands of dry regions in the northern hemisphere, no-till is widely practiced for soil moisture conservation and soil erosion control (Derpsch *et al.*, 2010). Similar practices are adopted for grain production in the “pampas” region of South America, where soil erosion control is an additional objective (Díaz-Zorita, Duerte and Grove *et al.*, 2002; Alvarez *et al.*, 2009). It has also been shown that conservation tillage promotes the formation of stable macro-aggregates and contributes to black soil structure improvements in northeast China (Fan *et al.*, 2010). On the other hand, a recent study assessing conservation agriculture and control of soil erosion in Brazil forecasts a continuous increase in the area with adoption of conservation agriculture by the year 2030, including no-till (Polidoro *et al.*, 2021). The exponential growth of no-till occurred on black soils with annual crops in the south region of Brazil, and crops in rotation or integrated systems with pasture and forest in the cerrado’s biome.

Benefits of the practice

CT system, including continuous mouldboard and disc-ploughing and the removal of post-harvest residues, has caused a significant loss of SOM and serious soil degradation in several black soil regions (Follett, 2001; Alvarez *et al.*, 2009). The ongoing land degradation has threatened sustainable crop production and even national food security (Liu *et al.*, 2010). To effectively reverse the degradation of black soils, no-till has been proposed to farmers as partial replacements for CT. Positive effects of no-till on soil health parameters have been widely documented and include major reductions in soil erosion and fuel consumption, reduced CO₂ emissions, and enhanced water quality, biological activity, soil fertility and production stability (Pretty, 2008; Derpsch *et al.*, 2010; Lafond *et al.*, 2011a). In black soil areas, studies have also reported better soil aggregation, higher SOC, and increased potentially mineralizable nitrogen (N) in no-till soils (McConkey *et al.*, 2003; Pikul *et al.*, 2009; Malhi *et al.*, 2009; Lafond *et al.*, 2011b). Lafond *et al.*, (2011b) observed that N uptake and yields in long-term (31 years) no-till exceeded those in short-term (nine years) no-till, suggesting that even after nine years, and possibly even after 31 years, no-till soils may still be in a soil-building

phase. Higher SOC retention in no-till was observed due to fungal mediated aggregate stabilization in no-till practice in a black soil region of northeast China (Ding *et al.*, 2011). Merante *et al.*, (2017) reported annual SOC increases by zero tillage and direct drilling (also known as no-till seeding) of 0.04 to 0.45 tonnes C/ha in different countries and regions. Meanwhile, microbial biomass and nematode abundance and the alteration in their community composition at the micro-niche within aggregates could contribute to the higher SOC sequestration under no tillage (Zhang *et al.*, 2013).

The effect on no-till on crop yields vary, depending on crop species and weather conditions (Malhi and Lemke, 2007). No-till often increases crop yields and water use efficiency under dry conditions, but can result in reduced yield under wet conditions (Azooz and Arshad, 1998; Arshad, Soon and Arooz, 2002). However, in the tropical mid-latitude black soils of Brazil, no-till has been successfully implemented into a cropping system that has intense, erosive rains that occur normally at the start of the planting season (Freitas and Landers, 2014). Furthermore, studies have also showed the potential to mitigate greenhouse gas (GHS) emissions in areas converted to agriculture by using systems with legume-based crop rotations combined with no-till (Pillar, Tornquist and Bayer, 2012). No-till systems based on the use of herbicides can favor the development of glyphosate-resistant weeds, mainly in low intensity rotations (Johnson *et al.*, 2009). Sustainable management of black soils through no tillage can address main soil threats such as SOC and biological loss, erosion, compaction and nutrient imbalance.

Recommendations and potential barriers for adoption

There are environmental conditions that limit the effectiveness of the no-till seeding system. As mentioned previously, excess moisture that does not allow the seed bed and rooting zone to aerate can be problematical. Currently, the timing and length of this period of aeration is not well understood. Obviously, seeding is delayed and restricted when the seed bed is saturated during seeding. Soil temperature during germination and emergence can also be delayed in some crops such as maize (Licht and Al-Kaisi, 2005; Vyn and Raimbault, 1993), in black soil regions with temperate or cold climates.

In resource-limited cropping systems, it may take an extended period of time for the soil to reach an equilibrium before releasing a similar level of nutrients to the crop as is achieved through tillage. Reduced N mineralization under no-till may also reduce yields where N is limiting (Campbell *et al.*, 2001). Currently, organic cropping systems utilize tillage for weed control.

No-till strip tillage

Description of the practice

Strip till is a tillage system that combines no-till and full tillage to produce row crops (Nowatzki, Endres and DeJong-Hughes, 2017), and is commonly implemented in the black soil areas of the world. Narrow strips 15 to 30 cm wide are tilled in crop stubble, with the area between the rows left undisturbed. Often, fertilizer is injected into the tilled area during the strip-tilling operation. The tilled strips correspond to planter row widths of the next crop, and seeds are planted directly into the tilled strips. Strip tilling normally is done in the fall after harvest, but it also can be done in the spring before planting, where global position system (GPS) guidance is usually required to create the strips and seed the row crop into the strips (Photo 4.1.1c).





Photo 4.1.1c Strip till, Indian Head of Canada

Range of applicability

Strip till can be applied worldwide in arable crops, preferably on relatively flat land with poorly drained black soils. This type of tillage is performed with special equipment and can require the farmer to make multiple strips, depending on the strip-till implement used, and field conditions.

Benefits of the practice

Strip till warms the soil and allows aerobic conditions and a better seedbed than no-till. Strip till allows the soil's nutrients to be better match the plant's needs, while still giving residue cover to the soil between the rows. Strip tillage reduces bulk density and soil resistance to root growth while increasing the amount of biopores and soil water filtration rate (Laufer *et al.*, 2016). It also improves soil aggregate stability (Garcia-Franco *et al.*, 2018), which all together makes soils less prone to erosion (Dick and Gregorich, 2004). Strip tillage has several advantages in protecting and conserving black soils over CT and seeding systems while maintaining grain yield in row crops. The crop residue maintained on the soil surface between the cultivated strips also maintains SOM. In conclusion, soil erosion, nutrients imbalance, and compaction can be addressed by no-till strip tillage.

Recommendations and potential barriers for adoption

Strip tillage has an advantage over no-till in environments when early seeding results in reduced soil temperatures, and delayed and reduced plant emergence compared to traditional tillage operations. Under these environmental conditions strip till removes the negative impact on yield observed in a no-till seeding system (Licht and Al-Kaisi, 2005). The effect of these depressed yields with no-till are only observed in a few crops, the predominate one being maize. This has limited the development of no-till on black soils where maize is the predominant crop.

4.1.2 Soil organic cover

Cover crops

Description of the practice

Cover crops are defined as a “close-growing crop that provides soil protection, seeding protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. When plowed under and incorporated into the soil, cover crops may be referred to as “green

manure crops” (SSSA, 2008). Cover crops are also called “living mulch” or “green manure”. In some cases, cover crops can remain permanently on the soil, which constitutes a living soil cover. There are many cover crop practices implemented in black soil area around the world. Typically, cover crops are grasses, legumes, brassicas or mixtures of two or more species (Jian *et al.*, 2020). In Manitoba of Canada, alfalfa, red

clover and winter pea were consistently established as spring-seeded relay crops in fall-seeded winter cereals (Thiessen Martins, Entz and Hoepfner, 2005; Cicek *et al.*, 2014; Blackshaw, Molnar and Moyer, 2010). In the Republic of Moldova, mixtures of grasses, alfalfa, steppe ryegrass and sainfoin are used as cover crop practices to improve soil quality and crop yield (Leah and Cerbari, 2015; Rusu, 2017) (Photo 4.1.1a).



Photo 4.1.2a Hairy vetch as cover crop, Salto, Argentina

Range of applicability

Cover crops can be a good practice for sustainable black soil management and needs to be adapted to the farming system, black soil types and climate. Double cropping, the production of a second crop after the first crop has been harvested, provides an opportunity to utilize late-season moisture and heat resources after the harvest of the cash crop. Early maturing crops, including annual forages or winter cereals can provide a window of opportunity for double cropping with cover crops (Thiessen Martens and Entz, 2001).

Benefits of the practice

Annually, no-till cover crops can sequester between 0.1 and 1 tonne SOC /ha relative to no-till depending on cover crop species, soil type, and precipitation

input (Merante *et al.*, 2017; Poepflau and Don, 2015). Soil cultivated with perennial grass mixture (alfalfa + ryegrass and sainfoin + ryegrass) for 4 to 6 years, led to positive changes in SOM content and favorable modification in physical and chemical properties (Leah and Cerbari, 2015). In addition, the use of cover crop systems has allowed to moderate soil moisture and near-surface air temperature (Thiessen Martins, Hoepfner and Entz, 2001; Kahimba *et al.*, 2008). This effect has implications for snowmelt infiltration, depth of frost, and probably also for pest cycles and nutrient cycling. Cover crop management increased the soil water transport and water retention in black soils, as compared with bare soil rotations (Villarreal *et al.*, 2022). In this sense, a cover crop could be a

suitable management in order to recover soils in terms of increasing of soil water transport compared with the soybean monocropping system in Mollisols in Argentina Pampas region (Villarreal *et al.*, 2022). Moreover, other studies reported that cover crops such as alfalfa, red clover and winter pea can reduce soil moisture in black soils in Canada in the case of an excessive moisture (Blackshaw, Molnar and Moyer, 2010; Kahimba *et al.*, 2008; Thiessen Martens, Hoepfner and Entz, 2001). As cover crops contribute to moisture regulation, their use can be a benefit in wet years as well as in dry years. When legumes were used as cover crops, yield benefits to the subsequent crop were observed in all studies. In addition, weed suppression was observed by the alfalfa cover crop in the study conducted in Canada in winter cereals (Blackshaw, Molnar and Moyer, 2010). In organic farming, the use of fodder mixtures as cover crop is achieved with low consumption of fertilizer and without herbicides, which also has a positive economic impact (Leah and Cerbari, 2015). In summary, cover crops are a good practice to address SOC and biodiversity loss, compaction, and soil nutrients imbalance.

Recommendations and potential barriers for adoption

After the main crop has been harvested, the consistent establishment of a second crop can be difficult in many black soils regions due to extremely variable precipitation during this period (Thiessen and Entz, 2001). In southern Manitoba, researchers have successfully established a second crop after a winter cereal over several years of research; however, biomass production has been extremely variable, ranging from 95 to 2 357 kg/ha for double cropped black lentil, hairy vetch, and field pea; biomass production achieved at least 1 tonne /ha in only a few instances (Cicek *et al.*, 2014; Thiessen and Entz, 2001). Soil moisture and microclimate can be impacted by late-season cover crops. For example, if the subsequent season is

drier, then the cover crop will compete with the main crop for the available water content, thereby creating soil moisture stress. This, in turn, will affect the crop performance and yield (Kahimba *et al.*, 2008).

There is evidence that an integrated long term strategy and plan which include all relevant sectors are key to achieve cover crop management and its benefit on soil quality and production. For example, in the Republic of Moldova, perennial cover crop of grasses, alfalfa, steppe ryegrass and sainfoin are used to improve soil quality and crop production of fodder. The practice can be implemented only when at least 15 percent of agricultural land used for restoring the livestock sector and perennial grasses (Leah and Cerbari, 2015).

Organic mulch

Description of the practice

Organic mulch involves the application of specific material on the soil surface in order to reduce water loss and soil erosion (which is the biggest challenge of black soils management) but also to suppress weeds, reduce splashing, modify soil temperatures and generally improve crop productivity. Organic mulches would entail any material such as straw, leaves or loose soil, etc. that is spread or formed upon the surface of the soil to protect the soil or plant roots from the effects of raindrops, soil crusting, freezing, evaporation, etc. (SSSA, 2020). In the Republic of Moldova, main mulch practice is shredding and spreading plant residue uniformly on the soil surface after harvest with N fertilizers (mineral or organic) at a depth of 6 to 10 cm. Meanwhile, plowing should be performed as late as possible, especially in October and November (Rusu, 2017). In Chinese black soils, a no-till management scheme with different quantities of maize straw mulching is being implemented in the field (Yang *et al.*, 2020) (Photo 4.1.2b).



Photo 4.1.2b Organic mulch, Lajitas, Argentina

Range of applicability

The use of mulches based on crop residues is applicable to any type of pedoclimatic context. Black soil areas with higher net primary productivity are less constrained in having enough crop residues such as maize, soybeans and wheat, to keep the soil completely covered with crop residues.

Benefits of the practice

The use of crop residues as mulches implies several benefits on soil properties. Straw mulching significantly increased the soil water content and SOC, soil total nutrients and soil microfauna (Deng *et al.*, 2021; Yang *et al.*, 2020). Furthermore, the effectiveness of mulching in reducing soil erosion was observed in Ukraine, where minimum tillage with 2.5 tonnes/ha of mulch in Mollisols increased available water, reduced runoff up to 3.8 m³/ha and improved spring barley yield by 1.6 tonnes/ha (Hospodarenko, Trus and Prokopchuk, 2012). This trial also showed that straw mulching leads to a significant decrease of weeds, thereby decreasing the use of herbicides (Sun *et al.*, 2016).

In past decades, the C balance of Mollisols in croplands has been negative due to soil erosion, degradation, and other improper management (Xu *et al.*, 2020). An application of low quantity maize stover with a high frequency of mulching in major Mollisols areas of the world, compared to low frequency maize stover mulching, lead to significant increases in yield, SOC, total nitrogen, total phosphorus, and total potassium. This will contribute significantly to food production and climate change regulation (Yang *et al.*, 2020). Generally, organic mulch can address the soil challenges in terms of the SOC loss, soil erosion, and nutrient imbalance.

Recommendations and potential barriers for adoption

Maintaining a low quantity but high frequency of mulch might efficiently boost soil health without compromising crop yields and as well optimize the use of stover. Applying a small quantity of stover mulching at high frequency might be sufficient for regenerative agriculture by efficiently improving soil health. When

the stover quantity was limited, using small quantities for multiple additions can regenerate more stable and active bacterial communities, and result in greater soil fertility. Hence, applying a small quantity of stover mulching at high frequency might be sufficient for regenerative agriculture by efficiently improving soil health (Yang *et al.*, 2020).

An excessive amount of crop residues in specific pedoclimatic conditions can be counterproductive for grain yield. Mulches can lead to allelopathy, a common biological phenomenon by which one organism produces biochemicals that influence the growth, survival, development, and reproduction of other organisms, that reduces crop growth, lower soil temperatures that impede fast establishment of crops (Venterea, Maharjan and Dolan, 2011), as well as exacerbation of frost damage (Snyder and Melo-Abreu, 2005).

In general, to make progress when using mulch, it is not only necessary to adopt multidisciplinary thinking and effective integration of multiple viewpoints from scientific research and practical orientation from farmers, but it is also important to include effective cooperative actions to formulate policies for more regenerative agriculture and a more promising future (Sherwood and Uphoff, 2000).

4.1.3 Nutrient management

While black soils are inherently fertile, with a generally high SOM content (FAO, 2020), effective nutrient management is still critical for soil health, food security and environmental protection. The loss of SOM in black soils leads to the loss of related nutrients, such as N, P and K. However, many black soils also suffer acidification processes and loss of exchangeable bases and many essential micronutrients such as Zn. If these nutrients are not replenished, the ability of black soils to produce food may be affected. Nutrient management involves using nutrients as efficiently as possible to improve productivity while protecting the environment. Nutrient management depends on soil fertility, physical and biological as well as climate conditions, but one key principle behind nutrient management is balancing soil nutrient inputs with crop requirements. Achieving this balance, in essence, will lead to increased productivity and farm profitability, while at the same time, minimize nutrient losses to the environment. It is well-known that nutrient cycling in agroecosystems is a function of

biotic (mineralization controlled by living organisms) and abiotic factors (physical or chemical including climate). Here, we describe some of the major issues and challenges related to nutrient management in black soils.

Manure additions

Description of the practice

Manure includes the excreta of animals raised for meat or other products whose chemical composition depends on the diet and the type of animal from which it originates (such as poultry, cows, sheep, horses and rabbits) and may also include the plant material (straw) used as bedding for animals. Manure can be found in liquid (liquid manure or slurry) or solid (solid manure) form. Manure can add essential plant nutrients (nitrogen, potassium, and phosphorus, collectively known as NPK) to the soil and improve soil quality. While partial substitutions of mineral fertilizers with manure can enhance crop yields, the complete replacement of mineral fertilization with manures can have detrimental effects on crop yields (Photo 4.1.3a).





Photo 4.1.3a Manure addition, Harbin city of China

Range of applicability

The use of manure is widely practiced among different climates, crop types, and in conjunction with other techniques such as the addition of synthetic fertilizers, type of tillage, and irrigation according to various black soil regions in our world. For instance, livestock manure and crop straw are the main components of organic fertilizer sources in China (Li, Liu and Ding, 2016). In North America, biosolids and slurries from municipal and industrial sources are also used.

Benefits of the practice

Manure application decreases soil bulk density, improves aggregate stability, and increases organic matter contents, phosphorus, bacterial and archaeal diversity, and infiltration in soils. Return of organic manure was a favorite measure to maintain or increase the content of SOC and its individual fractions, thus improving soil quality and crop production in black soil areas (Han *et al.*, 2006). In the long term, application of manure, whether as a stand-alone treatment, or combined with mineral fertilizers, results in increased levels of all forms of phosphorus (total, organic and mineral fraction) and soil fertility in general. This increase is most pronounced in the surface layer,

which serves as a nutrient deposition zone, in black soils of Serbia (Milić *et al.*, 2019). Inorganic fertilizer and manure amendment alter the soil bacterial and archaeal community. In black soils of northeast China, the incorporation of inorganic fertilizer and manure increase soil bacterial and archaeal diversity (Ding *et al.*, 2016). Applications of manure were not enough to significantly increase the cumulative water infiltration into the black soils although a trend towards increased infiltration and exchange cations with manure application was observed (Assefa *et al.*, 2004).

The addition of fresh or composted manure promotes the growth and yield of vegetables, grains, and forage. In the northern part of black soil area in China, the management of manure is critical to improve crop production. The optimum management for maize and wheat production was to apply chemical fertilizer and manure without irrigation, but for soybean, it was to apply fertilizer and manure with irrigation (Liu *et al.*, 2004). In the Serbian black soil area, application of farmyard manure along with inorganic fertilizer had significant effect on grain yield in the investigated periods (Milić *et al.*, 2019).

The addition of manure improves the physical conditions and availability of organic carbon to support microbial processes that regulate nitrification and methanogenesis. For instance, increasing SOC, the greenhouse effect may be alleviated by sequestering more CO₂ in black soils of northeast China (Han *et al.*, 2006). Legumes and green manure are important for enhancing biological processes and increasing N availability in black soils, resulting in economic and environmental benefits in Ukraine (Baliuk and Miroschnyenko, 2016). The practice can successfully address threats such as SOC and biodiversity loss, nutrient imbalance and compaction if sustainable used.

Recommendations and potential barriers for adoption

Recycled organic manure along with appropriate chemical fertilizers is strongly recommended for the black soil area (Han *et al.*, 2006). The effect of manure application on soil chemical and physical properties in these soils is variable depending on soil and manure type. Salinity and sodicity assessment should be part of a monitoring programme on manured lands to ensure that soil quality and productivity are not adversely affected over the long-term by repeated manure applications (Assefa *et al.*, 2004). Addition of fresh manure should come with a caution because fast decomposition of fresh manure could produce soil warming and result in damage to plant roots. Manure adds N to soils and can lead to N₂O emissions, but by

replacing chemical fertilizers, manure application can mitigate N₂O emissions to a certain extent (Guo *et al.*, 2013). The use of manure requires adequate logistics in terms of storage sites, avoidance of contamination of water and requires the availability of machinery. A total replacement of synthetic fertilizer sources by manure should be considered carefully, at least for agriculture that is carried out over large areas.

Compost application

Description of the practice

“Composting is the biological decomposition of organic materials by microorganisms under controlled, aerobic conditions to a relatively stable humus-like material called compost”. Thus, the application of compost on the soil can increase SOC and provide nutrients to soils. Well-prepared compost features a humus structure of stable aggregates and clay-humus complexes which improve the soil structure (Misra *et al.*, 2003). Through composting, biomass found on-farm can be reused, thus potentially avoid rotting and GHG emissions from crop residues, manure, leaves, etc. Compost can be made out of very different ingredients (such as manure, crop residues, biowaste and kitchen waste) and it is widely used among farmers, especially smallholder farmers. Different composting methods exist, mainly aerobic and anaerobic composting (Misra *et al.*, 2003) (Photo 4.1.3b).



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Photo 4.1.3b Compost, Jinlin province of China

Range of applicability

The practice can be applied in any climatic region of black soils except in extreme cold or arid environments.

Benefits of the practice

Compost improves the soil structure through the formation of stable aggregates. Likewise, it regulates soil moisture and increases SOC, fertility, microbial and faunistic diversity of black soils. Consecutive applications of municipal sewage sludge composts improved the soil nutrient status, by adding slowly decomposing organic matter abundant in macronutrients (N, K and P) without causing excessive leaching of nitrate into the groundwater in black soils of Hungary (Farsang *et al.*, 2020). In Japan, the change of microbial biomass in Andosols and Chernozems was faster under the compost-compound fertilizer mixture (CCFM) than under the chemical fertilizer or control treatments. CCFM tended to enhance plant growth in both soils. Compost-compound has a soil carbon storage effect with less resultant GHG emissions, especially in Andosols (Sato *et al.*, 2022). In the Chernozem region of the Russian Federation, complex compost composed of the waste products

of the agriculture (cattle manure and plant residues) and chemical fertilizer (phosphogypsum) improved aggregation in the plough layer and decreased soil bulk density. The water and air properties of the black soils can also be optimized, which was seen from an increase in the field and total water capacity, total porosity, and soil water storage (Belyuchenko and Antonenko, 2015). Regarding soil biodiversity, compost addition led to significant improvement in the soil fertility, while there is a positive effect on the abundance of ammonia oxidizers and denitrifiers. Compost addition play crucial roles in shaping microbial community compositions and co-occurrence networks in black soils of northeast China (Yang *et al.*, 2017).

In the aspect of yield, compared to unfertilized controls, frequent compost application resulted in higher yields. The complete use and composting of available farm biomass (such as crop residues, green waste and manure) can also reduce the rotting and thus GHG emissions. Using a good quality compost regularly (annually or for each cropping season) can reduce the need for application of chemical fertilizers. In conclusion, the compost approach is a practice that

addresses the black soil challenges such as nutrients imbalance, SOC loss, and soil biodiversity losses.

Recommendations and potential barriers for adoption

Using soil residual extractable P after ryegrass removal was high for fish-derived amendments and the commercial product, but the potential risk of P pollution needs to be considered when these are applied according to N requirements in black soils (Laos *et al.*, 2000).

An increase in the sorption potential of the organic mineral complex can decrease in the content of mobile forms of heavy metals in compost. Assessing the content of highly toxic metals in the upper layer of leached chernozem after harvesting is necessary to identify the concentration of heavy metals (Antonenko *et al.*, 2022). Composting animal manure, sewage sludge and wastes from the wine making industry and factories for soil fertilization. Application should be carried out according to the period and conditions of management (Rusu, 2017).

Chemical and mineral fertilization

Description of the practice

Even Black soils generally hold high soil fertility, but high intensive production pose a dangers in soil fertility reduction in those soils. Sufficient but not excessive use of fertilizers is necessary to maintain black soils. In addition, strategies that enhance SOM content and reduce overall soil degradation are vital to enhancing soil nutrient supply power in the black soil areas of the world (Campbell *et al.*, 1991, 2001; Malhi *et al.*, 2011a; 2011b; Castañeda-Martin and Montes-Pulido, 2017).

There is a wide range of nutrient sources that are used in black soil regions. The most commonly used N fertilizer source is urea. Other chemical N fertilizer sources include calcium ammonium nitrate, ammonium sulphate, urea ammonium nitrate, anhydrous ammonia, and diammonium phosphate. Due to advances in fertilizer technology, coated fertilizer products that release nutrients slowly to the soil are also being used (such as environmentally smart nitrogen). While these coated products have shown great promise in reducing N₂O emissions and nitrate leaching during the growing season (Gao *et al.*, 2015; Gao *et al.*, 2018), N losses in the non-growing season may be elevated due to high residual soil mineral N content due to slow or delayed release of N (Clément *et al.*, 2020; Zvomuya *et al.*, 2003). Moreover, the associated cost and more or less inconsistent crop yield benefits have hindered widespread adoption of coated fertilizer products. In addition to this, products that utilize a urease or nitrification inhibitor are also used, but on a smaller scale (Amiro *et al.*, 2017).

Major chemical fertilizers used for P include monoammonium phosphate and superphosphate, while potassium chloride is the most widely used source of K. Sulphur (S) is applied in black soils as elemental S (the most commonly concentrated form of S), sulphate form (SO₄²⁻) in sulphate-based fertilizers or a combination of both. S fertilizers used in black soils of Canada are ammonium sulphate, urea-ammonium sulphate, and sulphur bentonite. Other products that contain elemental S, as well as both elemental and sulphate-sulphur are also used in black soil areas such as Canada and China. In some regions, gypsum may also be used as an S source, particularly in organic production (Photo 4.1.3c).





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Photo 4.1.3c Nitrogen and phosphate fertilizers application, Indian Head of Canada

Range of applicability

The use of inorganic fertilizers has risen globally from 1960 to 2020. The growth of fertilizer use has been high in black soil regions of Asia. Fertilizer use increased across all the black soil regions including east Europe, northeast Asia, North America and South America. Over 80 percent of globally used fertilizers are made up of N, P and K whose 2020 cumulative demand was estimated at 115.3 million tonnes of N, 56 million tonnes of P and 36.7 million tonnes of K (FAO, 2020). For instance, chemical fertilizer is the main source of farmland nutrient input in China. In 2015, the consumption of chemical fertilizer in China reached 60.2 million tonnes, with the black soil area in the northeast accounting for 10.6 percent of the national fertilizer consumption (Li, Liu and He, 2017; Li, Liu and Ding, 2016).

Benefits of the practice

In comparison to a few studies where SOC was revealed to maintain or decrease after long term fertilizer application in black soils, other studies showed that additional manure application and optimized macro nutrition fertilization can increase SOC (Xie *et al.*, 2014; Ding *et al.*, 2012; Abrar *et al.*, 2020; Manojlović *et al.*, 2008; Russell *et al.*, 2005). Fertilizers also play

a crucial role in improving the soil chemical properties and processes replacing deficient nutrients (macro and micronutrients). Among other functions, the basic cations (K^+ , Ca^{2+} , Mg^{2+}) that are added with fertilizers are crucial for managing soil acidification. High ammoniacal nitrogen and sulfate fertilizers produce acidic reactions with a neutralizing effect on soil alkalinity.

Mineral fertilizer affects the physical properties of black soils. A combination of mineral fertilizers and organic manure and biochar can enhance the sequestration of SOC and improve soil physical environment such as aggregation and compared to the pure organic manure and mineral fertilizers in black soil regions (Chen *et al.*, 2010; Campbell *et al.*, 1986). It is important to note that in most cases inclusion of organic resources like manure resulted in better physical properties compared to mineral fertilizers.

Most of the biological benefits of fertilizer, including the micro, meso and macrofauna activities and processes are associated with SOM (Haynes and Naidu, 1998). Long-term studies have shown that application of NP and NPK fertilizers in addition to secondary and micronutrients reduce soil fungal, bacteria biodiversity and changed community composition in black soils of China (Zhou *et al.*, 2016; Wei *et al.*, 2008).

Globally, over 40 percent of crop yield is attributable to inorganic fertilizer nutrient inputs (Stewart *et al.*, 2005). The grain yield of most cereals could be doubled by applying the recommended rates of macronutrients as mineral fertilizers as well as in black soil regions (Pepo, Vad and Berényi, 2006; Kostić *et al.*, 2021; Campbell *et al.*, 2001; Liu *et al.*, 2001).

Sustainable use of mineral fertilization can address nutrient imbalance issues of black soils, but also can ease threats such as SOC loss and biodiversity losses if sustainably used.

Recommendations and potential barriers for adoption

Due to the dynamic nature of N, its content is highly variable in both space and time. For example, soil nitrate-N measured after harvest in fall autumn over a 12 year period in a semi-arid environment in the Canadian black soils varied from 21 to 44 kg N/ha, thereby significantly affecting N fertilizer application rates (St. Luce *et al.*, 2020). In black soils of northeast China, a study found that high levels of N fertilizer, 190 Kg N/ha and above, applied in the spring resulted in a large increase of soil nitrate-N at depth in the soil, demonstrating the need to manage N application rates to protect both ecological and soil health (Cai, Mi and Zhang, 2012). In addition, there is tremendous risk of acidification due to the widespread use of chemical N fertilizers. Application of nitrate-based rather than ammonium-based fertilizers can help to reduce fertilizer-induced acidity of black soils (Engel *et al.*, 2019).

An essential component of effective nutrient management is timely diagnosis of soil nutrient status. Soil testing is therefore a critical decision support tool for effective fertilizer management. It provides information on the nutrient balance and together with nutrient removal rates, will help guide fertilizer recommendations. Fertilizer application should take place at seeding or just prior to it. However, fertilizer application in late fall prior to soil freezing is quite common, especially with anhydrous ammonia (Tenuta *et al.*, 2016). Meanwhile, banding of N fertilizer has been shown to significantly reduce denitrification, ammonia volatilization, nitrate leaching, and increase N use efficiency (Gao *et al.*, 2015; Malhi *et al.*, 2001). Soil N supply is governed by N mineralization during the growing season and has proven difficult to accurately predict due to the complexity of this process, which is influenced by many biotic and abiotic factors. Nevertheless, in most countries, estimates of

N requirements for various crops are available, which vary with soil type, local climatic conditions and other factors. These recommendations need to be periodically updated to account for varietal improvements through breeding, and changes in soil and crop management.

Technological advances in equipment, software and data processing including cost-effective sampling design and predictive soil mapping using machine learning, have provided more opportunities for measuring and monitoring plant nutrient and soil fertility, and overall health of black soils. Assessments as well as high-throughput laboratory techniques can rapidly and accurately assess several soil parameters that are integral for nutrient management in black soils. However, regional calibration data has to be collected in addition to existing global spectral libraries or soil libraries from countries and regions. The development of calibrations on black soils is a valuable line of research, with much to gain in terms of monitoring their degradation due to increasing pressures for food production and climate change.

Economic, social and physical limitations can hinder the adoption and implementation of sustainable fertilizer management and 4R principles. Interactions between producers and local agronomists, certified crop advisors, or researchers are instrumental in the adoption of the principles (Amiro *et al.*, 2017). Bruulsema, Peterson and Prochnow (2019) further suggested that the adoption and implementation of the principles “depend on engagement between science and industry not only at the farm level but along the full agricultural value chain”.

In general, unlike other soils that require mineral fertilizers to be put into production, the black soils have a high fertility which means that they have high amounts of nutrients related to organic matter, such as N, P and K. In spite of this, the high production pressures that operate on black soils determines the need for nutrient replenishment, since many black soils already show signs of depleted fertility. Currently, black soils not only require adequate fertilization plans, but also the local adjustment of response models to the fertilization of the main crops produced, such as wheat and maize.

Biochar

Description of the practice

Biochar is a relatively recent term, used to name charred organic matter when it is applied to soil in a deliberate manner, with intent to improve soil properties and long-term carbon sequestration (Lehmann and Joseph, 2015). Pyrolysis is the most common technology employed to produce biochar. Biochar can and should

be made from biomass waste materials. In black soil regions, biochar has been produced from maize and soybean straw or woodchip, but is normally added

with manure or mineral fertilizers (Han *et al.*, 2019; Chaturika *et al.*, 2016; Yao *et al.*, 2017; Banik *et al.*, 2021) (Photo 4.1.3d).



Photo 4.1.3d Biochar application, Hulin city of China

Range of applicability

The addition of biochar to agricultural soils is receiving much attention due to the apparent benefits to soil quality and enhanced crop yields in black soil regions, as well as the potential to gain carbon credits by active carbon sequestration. The diverse physical and chemical characteristics of biochar make it a compelling and useful substance in a variety of applications, from smallholders to large-scale farming. It should be noted that biochars vary widely in properties depending on the feedstock and production conditions, so suitable biochar should be chosen to address the specific black soil constraints for each intended application. For instance, Charcoal, also known as black carbon or biochar, to refer to its soil quality enhancing properties and to deflect the link between charcoal, fire and forest loss, is considered a major contributor to the fertility of black soils in central Amazon (Glaser and Birk, 2012).

Benefits of the practice

Biochar contains organic matter and nutrients, and its addition can increase organic carbon, pH, total nitrogen, available phosphorus (P), available potassium (K) the cation-exchange capacity (CEC), readily available water (RAW) content, and decreased bulk density (BD).

In a Midwestern Mollisol of the United States of America, biochar application significantly increased soil pH, RAW content and SOC, availability of macro and micronutrients, and bulk density (Rogovska, 2014; Banik *et al.*, 2021). The manure-biochar incubation enabled biochar can stabilize the carbon and several nutrients from manure. The subsequent manure biochar mixture application to soil improved soil quality and plant nutrient availability compared to conventional manure application. In black soil region of northeast China, besides soil quality improvement by biochar amendment in terms of SOC, soil water, bulk density

and available nutrition, soil bacterial community dynamics can also be shifted by biochar input and crop straw management, for example, soil fungal abundance increased with biochar addition (Qiao *et al.*, 2020; Yao *et al.*, 2017). In Canada, biochar application is not a practical management approach for improving soil fertility and nutrient cycling in surface Chernozems. Nevertheless, co-applying biochar with NP fertilizer appears to improve soil P availability in the short-term in Raymond and Lethbridge of Canada (Romero *et al.*, 2021).

Biochars could be used to solve both environmental and agronomic challenges and further improve the sustainability of animal and crop production agriculture. Biochar application can increase grain yield by 11 to 55 percent following very high stover application rates, presumably because biochar mitigated adverse effects of allelochemicals released from the decomposing maize residue. But during a severe drought, the effect of biochar on maize yield was limited (Rogovska, 2014). The result of a three-year project showed that the application of maize-straw biochar at a rate of 15.8 and 31.5 tonnes/ha had positive effects on crop yields in black soil areas (Jin *et al.*, 2020).

Inputting biochar benefits soil health through minimizing soil threats including SOC and biodiversity loss, compaction, nutrients imbalance.

Recommendations and potential barriers for adoption

Knowing the limiting factors of agricultural production in black soils of the country and understanding whether the desired results can be obtained with biochar is critical. Main characteristics of biochar must be considered when planning inputting biochar for its agronomic use, because once distributed, it cannot be removed from the soil. For example, research has indicated that application of corn straw biochar to soil at the rate of 400 g/kg can significantly increase soil pH, EC and resulted in decreases in CEC and exchangeable Ca^{2+} in comparison to untreated soil, then enhance soil salinization risk in black soils of northeast China (Meng *et al.*, 2021). To achieve the goals of biochar application discussed above, the choice of application methods depends on its physical and chemical properties as well as application amount.

The scale of production can be very different (medium, agricultural scale, kitchens) with very variable current costs. Optimal use of new technologies is only possible if they are rapidly adopted and widely disseminated. Although the increased yields of biochar production

may be a boon to the new agricultural technology, the high costs can be a deterrent. As a result, before the widespread promotion of biochar systems, it is important to investigate the economic implications of biochar systems compared to conventional systems. The cost of using biochar in agriculture depends on the biochar application rate, the cost associated with transporting the biochar from the production plant to the experimental field and the value that can be derived from the energy produced.

4.1.4 Crop diversification

Many areas covered by black soils are managed under extensive agriculture, based on two or three annual crops (such as wheat, maize or soybeans). This trend to limited crop diversity resulted in a loss of biodiversity and soil physical deterioration (Peralta, Alvarez and Taboada, 2021). Crop diversification is a suitable tool to avoid overly simplified agricultural models, and to improve the quality of soil structure. Diversifying the cropping system is already being practiced by agricultural producers to overcome crop production challenges, such as high land values, increased input costs, varying weather factors, and increased demands for new products. Especially in black soil areas, long-term monocropping system such as maize and soybeans that damage soil health and food security. Thus, sustainability concerns have raised interest in crop diversification among agricultural producers, especially throughout the black soil areas.

Crop diversification means growing more than one crop in an area. Diversification can be accomplished by adding a new crop species or different varieties, or by changing the cropping system currently in use. Commonly it can mean adding more crops into an existing rotation. It can also include an integration of crops and livestock, defined as mixed farming. Crop diversity encompasses several aspects, such as crop species diversity, varietal diversity within crop species, and genetic diversity within crop species. It is recognized as one of the most feasible, cost-effective, and rational ways of developing a resilient agricultural cropping system.

Crop rotation

Description of the practice

In black soil regions, farmers using different species (mainly legumes) as precedents of the main crop (most often winter cereals) resulted in some increases in grain yields and improvement of soil quality. Nowadays, crop rotations are a common practice and, in some

socioeconomic contexts are encouraged by agricultural policies in black soil areas. Scientific research has revealed that the benefits of this practice are due to

improved resources use efficiency, increased N supply by legumes, and the breaking of pest cycles (Ryan *et al.*, 2008) (Photo 4.1.4a).



Photo 4.1.4a Crop rotation (soybeans and wheat), Russian Federation

Range of applicability

The use of crop rotations in permanent croplands can be ubiquitous, although a high degree of crop diversity is usually hindered by pedoclimate and socioeconomic limitations in black soil regions. Low temperatures and snowfall during autumn and winter months restricts crop cultivation until spring. In turn, different soil characteristics can limit the range of crops to be chosen for rotation. A clear example is the role played by soil pH on some crops. For instance, legumes are well adapted in slightly acidic to neutral soils whereas they grow poorly in alkaline black soils.

As stated, socioeconomic factors also play a major role in the use of diverse crop rotations in black soil areas. Since the advent of industrialized agriculture and the availability of synthetic fertilizers, cereal monocropping (i.e., wheat, maize, rice and barley) have been dominant in black soil regions. The specialization of industrial farms to only a few commodities and the lack of financial support to invest in different machinery also impede adoption by farmers in black soil regions.

Benefits of the practice

Crop rotation is closely linked to the diversification of production models. The design of a rotation is determined by the availability of water and the agroclimatic characteristics. The areas covered by black soils are under the threat of very simple rotations, with a tendency to monoculture, which favours not only the

loss of fertility, but also the proliferation of resistant pests and weeds. It is necessary to design crop rotations with a greater presence of grasses (wheat, barley and corn), whose root system favours the development of stable aggregates in the soil. Specifically, soil physical properties are improved significantly when using diverse crops through a variety of mechanisms, which impact on soil structure. Some perennials such as alfalfa are used in the rotation system of black soil areas, as they have a tap-root able to reach to very deep soil layers, enhancing the use of remnant soil water and nutrients, reducing drainage and N leaching. Moreover, legumes such as soybeans present higher activity in the rhizosphere (the environment close to the roots where most of soil biological activity occurs) and greater root exudation.

Regarding soil chemical properties benefits of rotation practice, soybean rotated with other crops that produce high amounts of residue improved soil fertility and thus had good potential to increase soybean yield and profitability in black soil regions of the Russian Federation and Canada (Zentner *et al.*, 1990; Stupakov *et al.*, 2019). And a long-term research of crop rotation leading to an increase of the ratio Cha: Cfa in (humic acids to fulvic acids) has been observed in Ukraine (Hospodarenko *et al.*, 2018).

Crop rotations also lead to improved soil biological properties of black soils. In the case of the northeast China black soil region, soil bacterial communities

remarkably differed between maize monocropping and maize soybean rotation in both bulk and rhizosphere soils, and that bacterial abundance and community diversity were significantly higher in rotation than in monocropping. Compared with continuous cropping of soybeans, crop rotation increased bacterial abundance and diversity and altered the community composition both in the bulk and rhizosphere soils such as increased nematode abundance and their functional metabolic footprint (Zhang *et al.*, 2015; Liu *et al.*, 2017).

The benefits of crop rotations in terms of an increase in productivity for subsequent crops have been known in black soil regions. Crop rotations present different socioeconomic benefits. Inclusion of a grass legume forage crop or a legume green manure crop in the rotations with cereals produced consistent yield benefits. Yields of wheat grown on fallow after being cropped to legumes or grass legumes, and without the application of N or P fertilizer, were often higher than yields obtained in the well-fertilized monoculture wheat rotations. Furthermore, adopting diversified crop rotations, together with minimum and zero tillage management practices, will enhance non-renewable energy use efficiency of annual grain production in this sub-humid regions (Zentner *et al.*, 2004). For instance, the maize soybean rotation produced better yield and profitability, particularly in dry years, than monocropping system in the black soils of northeast China (Fan *et al.*, 2012). In the black soil region of Canada, soybeans that were rotated with other crops that produce high amounts of residue, improved soil fertility and thus showed good potential to increase soybean yield and profitability (Zentner *et al.*, 1990). In summary, crop rotations provide multiple benefits that can address soil threats in terms of SOC and biodiversity loss, nutrients imbalance, compaction and pollution.

Recommendations and potential barriers for adoption

One of the most dramatic effects of crop rotation on soil C is how maize tends to increase soil C while soybean tends to lower soil C. This is one reason why crop rotations in the United States of America mid-west was dominated by maize, and not soybeans, in order to capture the highest soil C contents. The black soil zone of Canada includes crops with a range of C contents and C:N ratios. The two dominant grain crops, wheat and canola, tend to have high C:N ratios. Substituting oats for wheat reduces the C:N ratio of the rotation since oat has more N in straw than wheat. Adding pulses such as peas and lentils to the rotation further decreases the C:N ratio. Soybeans is unique among grain legumes in that its residue is very high in C, much higher than pea or lentil.

Before establishing any crop rotation, the pedoclimatic limitations to the different crops must be analyzed and taken into account. Potential markets must be explored and, if possible, secured before establishing alternative or neglected crops. These last should be implemented in small fractions of the available land.

Perennial crop

Description of the practice

Perennial crops are crops that, unlike annual crops such as cereals, don't need to be replanted each year. After harvest, they automatically grow back. Many fruit and nut crops are naturally perennial. The perennial crops provide an option to diverse cropping system and benefit properties of black soils, and is being used in the black soil zone of Canada and the United States of America (Entz *et al.*, 2002; Ryan *et al.*, 2018) (Photo 4.1.4b).





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Photo 4.1.4b Perennial crops (Kernza), Canada

Range of applicability

The practice is applicable worldwide under a wide range of pedoclimatic conditions. The most suitable locations are those with degraded black soils on sloped land and ecologically sensitive areas that need to build soil health in terms of SOC, reducing erosion.

Benefits of the practice

Growing perennial grains for several years can regenerate soil health before rotating to annual crops. While growing perennial grains on sloped land and ecologically sensitive areas can reduce soil erosion and nutrient losses, hence providing both provide ecosystem services and supporting multifunctionality.

For example, perennial legumes in rotation also reduce energy requirements by adding significant amounts of N to the black soils.

One perennial crop innovation since 2002 is “Perennial wheat” or Kernza (*Thinopyrum intermedium*) (Dick, Cattani and Entz, 2018). Adapted Kernza lines have now been developed (Cattani, 2019), and are being grown on a limited acreage, sometimes as a dual purpose grain and forage crop. Kernza has a particularly large root system, which will add to subsoil C in black soil zone cropping systems (Pugliese, Culman and Sprunger, 2019). In conclusion, inclusion of perennial crops is a good practice to address soil erosion and SOC.

Recommendations and potential barriers for adoption

Strategies that enhance multifunctionality are expected to play a major role in addressing limitations associated with low grain yields. Some management strategies can be combined to achieve greater functionality, such as growing perennial cereals with legumes for grain and forage on land that is sloped.

Because perennial grains are fundamentally different from annual grain or perennial forage crops, farmers need new information about management practices to optimize their production. Functionally diverse perennial grain polycultures can also provide a high level of ecosystem services, but, research is needed to identify combinations of perennial grain crops that are compatible and production practices that minimize management complexity.

4.1.5 Water conservation techniques

Description of the practice

Agronomic practices that can be implemented to control water erosion on cropland include residue management, conservation tillage, contour farming, crop rotation and cover crops (Weesies, Schertz and Kuenstler, 2017). Under tropical black soils in Brazil, soil erosion from precipitation has been successfully reduced by combining crop rotation, no-till, and permanent soil covering (Freitas and Landers, 2014). Those agricultural practices were discussed in previous sections. There are also several different irrigation methods used by producers around the world including: intermittent irrigation in rice, which allows the water level in the paddy to drop to low levels before being replenished; traveling lateral sprinkler systems that irrigate large fields to reduce cost per unit area; this necessitates high instantaneous application rates to meet crop water requirements over the entire field (Sojka and Bjerneberg, 2017); sprinkler systems, particularly centre pivots that operate on variable slopes and topography. Slope direction relative to the lateral affects how runoff accumulates; and in drip irrigation, where water is directly applied to the crop roots using a pressurized pipe system (Photo 4.1.5).



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Photo 4.1.5 Drip irrigation, Kherson of Ukraine

Range of applicability

Both agronomic practices and irrigation systems practices are applicable to all black soils including arable lands, croplands, permanent crops and pastures. The structure of the vegetation in those practices determine their efficacy at a given location. They can be typically designed to achieve multiple objectives depending upon the land slope, topographic and climatic conditions.

Benefits of the practice

One of significant factors in the transformation of black soils is soil water management. It changes the main factors of soil formation, connections with the environment, and determines the subsequent evolution of soil cover. The specific changes depend on the quality and volume of soil water supply to the fields, climatic and hydrogeological conditions of irrigation development regions, the original properties of soils, irrigation equipment and technology, and current production practices. The changes can improve moisture supply, a positive balance of humus, macro and micronutrients, increased fertility, and balance soil pH (Baliuk *et al.*, 2017).

Intermittent irrigation in rice, increased storage of rainwater by reducing runoff water by 56 percent and reduced irrigation water use by 22 to 76 percent resulting in a 15 to 346 percent increase in water use efficiency (Avila *et al.*, 2015). The grain yield of the rice was not impacted by the irrigation method used in this study.

In traveling lateral sprinkler systems, sprinkler type, nozzle pressure, and nozzle size influence runoff and soil erosion by affecting application rate, wetted area, and droplet size. Low-pressure sprinklers, which reduce energy costs, have smaller pattern widths and therefore greater application rates (Jat *et al.*, 2009; Tahat *et al.*, 2020).

In drip irrigation, water is conveyed under pressure through pipe and released as drops or drips directly to soil on the field through emitters or drippers. The spacing between emitters depends upon the plant

spacing. Only the immediate root zone of each plant is wetted. Therefore, this can be a very efficient method of irrigation with a low risk for soil erosion. However, this is a very capital and labor intensive system.

To summarise, soil water management and irrigation approaches can provide good opportunities to address soil erosion, SOC loss, and nutrient imbalance.

Recommendations before implementing the practice

Managing the full range of water supply on black soils from drought to periodic flooding requires several different approaches. Excess moisture can reduce the timeliness of seeding, while no-till and residue can increase moisture retention and reduce soil temperatures. A crop such as maize is particularly sensitive to this problem but even other crops such as wheat and canola can also be affected. Even in regions that tend to have excess moisture at seeding, water management is important due to the high likelihood of the crop experiencing moisture stress at some point during the growing season. No-till often increases crop yields and water use efficiency under dry conditions but can result in reduced yield under wet conditions (Azooz and Arshad 1998; Arshad, Soon and Arooz, 2002).

In the regarding of traveling lateral sprinkler systems, application rates for centre pivot and lateral move irrigation systems often exceed the soil infiltration rate meaning that runoff is a potential problem. Besides the irrigation methods, the water resource quality should be also considered during the decision making procedure. For example research results showed that there has not been any major detrimental effect on soil due to irrigation, but constant control of the quality of water for irrigation was necessary, as well as constant monitoring of the chemical properties of the irrigated soil (Choudhary and Kharche, 2018; Bilanchyn *et al.*, 2021). In general, as the climate becomes more arid, there is increased effectiveness of no-till in maximizing water use efficiency and grain yield of crops grown on black soils. This trend does appear to hold true in the midlatitude black soils of South America.

4.1.6 Biomass management

Description of the practice

Generally, crop straw amendment (SAT) is considered as the most effective method to increase soil carbon storage and crop yield through biomass management, especially in flat fields (Photo 4.1.6).

Other beneficial practices for biomass management including crop rotation that providing biomass with a high C to N ratio and cover crops that providing good quality and quantity biomass to soils.



© Xingzhu Ma

Photo 4.1.6 Biomass management, Zhaoguan county of China

Range of applicability

Biomass use based on crop residues is applicable to any type of pedoclimatic context. Agroecosystems with greater net primary productivity pose fewer limitations to the availability of sufficient crop residues. Climate conditions such as temperature and soil moisture can impact biomass decomposition and seeding resulting in adjustment of biomass management practices. Besides this, in these and other regions the competition for crop residues for other purposes such as fodder, fuel or construction material further limits the potential to biomass management. The percentage of biomass that can be removed and returned differs as you move to wetter or dryer regions or a region with a shorter or longer winter.

Benefits of the practice

Surface residues due to biomass return can control erosion, but the amounts vary depending on soil texture and field slope. In the black soil zone, the amount of residues required to control water erosion increases with field slope, with estimates of 0.8 to 1.15 tonnes/ha on 6 to 9 percent slopes and 1.15 to 1.7 tonnes/ha on 10 to 15 percent slopes. Having the harvesting residue results in soil loss, particularly on fields with steep slopes (Gregg and Izaurralde, 2010). Harvesting residues decreases crop yields, under both conventional and conservation management, although less so under conservation management. Biomass retained provide higher soil C, total P, soluble and labile forms of inorganic and organic soil P compared with the biomass removed (Hao *et al.*, 2022; Li *et al.*, 2022). For instance, straw return influenced the dynamics of available nitrogen and phosphorus, and increased yield of crops (Zhang, Wang and Sheng, 2018). Labile organic carbon fractions were also more sensitive to different forms of straw return in Mollisol black soils (Li *et al.*, 2022).

Biomass management practice through rotation can optimize C:N ratios. In the black soil zone of Canada, the two dominant grain crops, wheat and canola, tend to have high C:N ratios. Substituting oats for wheat reduces the C:N ratio of the rotation since oat has more N in straw than wheat. Adding pulses such as peas and lentils to the rotation further decreases the C:N ratio. Soybeans is unique among grain legumes in that its residue is very high in C, and much higher than pea or lentil.

Biomass management has also been shown to moderate the near-surface soil and air temperature (Thiessen Martens *et al.*, 2001; Kahimba *et al.*, 2008).

Biomass management is a very crucial practice that can address many soil threats such as SOC and biodiversity

loss, erosion, nutrients imbalance, acidification, and compaction.

Recommendations before implementing the practice and Potential barriers for adoption

In black soils of cold regions, the returned straw in the soil cannot complete degrade. The rate of biomass return should be considered according to the ecological condition. Incompletely degraded straw in the soil could block the emergence of seeds in next crop season. Furthermore, biomass management can impact soil moisture and microclimate as well. Studies in Canada have reported that productive cover crops can reduce soil moisture (Blackshaw, Molnar and Moyer, 2010; Kahimba *et al.*, 2008; Thiessen *et al.*, 2001). Depletion of soil water by the biomass management can be a benefit in wet years.

4.1.7 Integrated systems

Organic cropping system

Description of the practice

Organic cropping can occur in any of the above cropping systems in black soil areas but two restrictions are added: no chemical pest control and no addition of mineral fertilizers to supply nutrients to the crop. These restrictions increase the skills needed to conserve black soils in an organic farming system. The traditional method to control weeds in an organic cropping system has been to add more cultivation for eradicating weeds to the cropping system, which can increase the risk of soil degradation. Currently, two approaches are being explored and implemented to mitigate this increased risk to the soil, reducing tillage and improving soil physical and biological parameters. Research on reduced tillage in organic cropping systems has been conducted in black soil regions (Vaisman *et al.*, 2011; Podolsky, Blackshaw and Entz, 2016). Tools, such as the blade roller, have allowed vegetation to be managed and organic crops to be no-till seeded for multiple years (Halde, Bamford and Entz, 2015) (Photo 4.1.7a).





Photo 4.1.7a Organic no-till farming system (barley and spring wheat), Manitoba of Canada

Range of applicability

There is a worldwide applicability as the pedoclimate limitations are identical to all forms of agriculture in black soil areas.

Benefits of the practice

Legume cover crops included in organic farming system of black soils are particularly useful at improving soil physical (e.g aggregation) (Stainsby *et al.*, 2020) and biological parameters (Lupwayi *et al.*, 2018), and can provide a slow-release form of N for following crops (Thiessen Martins, Entz and Hoepfner, 2005). Thorup-Kristensen *et al.*, (2012) found that the addition of green manure cover crops resulted in an almost doubling in the average soil exploration by active root systems. Greater soil exploration was linked to greater subsoil inorganic N content (Thorup-Kristensen *et al.*, 2012). To sum up, an organic cropping system benefits soil health and addresses soil biodiversity loss, nutrient imbalance, and compaction.

Recommendations and potential barriers for adoption

The current level of practices implemented to protect black soils in organic cropping systems vary greatly from region to region and farm to farm within a region. The management required to implement cropping practices to protect soils in organic farming tend to be higher than in most conventional systems; however, producers utilizing an organic production system tend to be highly motivated to protect and improve their soil. In conclusion, organic agriculture is adequate for the management of soils, but requires fertility management based on organic and biological fertilizers, as well as biological pest control. These requirements make it difficult to adopt on a large scale, as is the case for the extensive production of annual crops such as soybeans, wheat, and maize.

Grassland conservation and restoration

Description of the practice

A good part of the world's black soils was formed under the influence of grassland vegetation (Photo 4.1.7b). Being replaced throughout time to produce annual crops. The periodic rotation of these annual systems with pasture periods favours the black soils to recover their original fertility, at least as regards organic matter and the quality of the structure. Grazing intensity and the regulation of stocking rates have been identified as one of the most important management practices to maintain or improve the quality of black soils (Sollenberger *et al.*, 2012). Some of the most common methods of measuring grazing intensity are stocking rate (animals/ha for a specified period of time), forage allowance (ratio of forage mass (kg/ha) to animal live weight (kg/ha)), and grazing pressure (animal live weight kg/ha) to ratio of forage mass (kg/ha) (Allen *et al.*, 2011).



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Photo 4.1.7b Grassland conservation and restoration, Municipality of Quaraí, Rio Grande do Sul state, Brazil

Range of applicability

The practices are applicable worldwide under a wide range of pedoclimate conditions where black soils dominated. Grassland a cold temperate zone is particularly suitable to those practices such as the east European plain, central Great Plains of North America, and pampas in South American.

Benefits of the practice

Modifying grazing intensity can reduce soil erosion, improve ground cover, C sequestration and plant vigor (Sollenberger *et al.*, 2012; Zhou *et al.*, 2017). It is also important in managing water quality (Van Poolen and Lacey, 1979) and species diversity (Herrero-Jáuregui and Oesterheld, 2018). Forage species, which affected the time of water use during the season, had more impact on soil water content than grazing intensity (Twerdoff *et al.*, 1999b). However, higher grazing intensities tended

to have greater soil water content in the upper 7.5 cm of soil than lighter grazing intensities. This indicates that higher leaf areas observed in lighter grazing treatments utilized more soil water due to greater evaporative surfaces than heavier grazed treatments, which had lower leaf areas (Baron *et al.*, 2002).

The preference of different herbivores for grass, forbs and legumes can impact the species present in a pasture (Dumont *et al.*, 2011). Grazer effect on soil C storage exhibits substantial variability and depends on both herbivore assemblage and characteristics of grazed grassland (Chang *et al.*, 2018). This indicates that the interaction between herbivore type, plant species and grazing intensity may be region-specific and difficult to predict simple management practices over a wide range of environmental conditions.

Maintaining plant cover on a grazed landscape is important for protection of the soil, nutrient

management, and a healthy microbial diversity. Research in Colorado, United States of America on a shortgrass steppe found that soils under plants had consistently higher C and N mineralization rates and, in some cases, higher total and microbial C and N levels than soils without plant cover (Vinton and Burke, 1995). They also found that soils under bunchgrasses tended to have higher C mineralization and microbial biomass C than soil under the rhizomatous grass, *Agropyron smithii*.

In a soil conservation context, stocking method can be used to ensure that soil cover is maintained and to protect soils when in a fragile state such as compaction of water saturated soils during a period of the year.

Overall, SOC and biodiversity loss and nutrient imbalance can be minimized by the practice of grassland conservation and restoration.

Recommendations and potential barriers for adoption

Overgrazing occurs when plants are exposed to intensive grazing for extended periods of time, or without sufficient recovery periods. It reduces the usefulness, productivity, nutritional value for livestock and biodiversity of the land, and can lead to the loss of ground cover, compaction, and soil erosion and reduced soil health. In addition, overgrazing can increase the occurrence of invasive species such as *Eragrostis plana*, which take the place of high quality native forage plants in the pampas of South America (Focht and Medeiros, 2012). Overgrazing is currently occurring in many regions. In Mongolia, the number of livestock increased by 265.3 percent between 1961 and 2019 and 11 percent of the total pastures were overgrazed (Unified Land Fund Classification Report, 2019; Research Conference material, 2015).

On the black soils studied by Twerdoff *et al.*, (1999a), as grazing intensity increased so did bulk density, but the maximum bulk densities attained did not reach levels considered limiting to productivity or sustainability in either perennial or annual pastures. Compaction in the pasture soil surface (0 to 2.5 cm) increased rapidly early in stand life, but levelled out with increasing stand age (Mapfumo *et al.*, 1999; Twerdoff *et al.*, 1999a). It appeared that annual pastures compacted (between 0 to 10 cm more) more rapidly than perennials, but generally bulk density for both annual and perennial pastures followed a quadratic relationship with cumulative cow-days and leveled off after about 40 to 60 cow-days over years and grazing cycles. Since the production of biomass is important to protect and improve the soil, sites that are more productive with higher rates

of biomass tend to be more tolerant of the impacts of grazing intensity (Eldridge *et al.*, 2017; Schönbach *et al.*, 2011) and other management practices. Along with other management strategies, such as reseeding, weed control and prescribed burning, deferred stocking can furthermore improve the response of desired vegetation and, over time, increase animal production potential (Allen *et al.*, 2011). Other stocking methods can be utilized to address specific issues in specific environments (Bailey, McCartney and Schellenberg, 2010).

In this section, we presented a global-scale assessment of sustainable practices for promoting black soil health, ensuring food security, mitigating climate change and overcoming constraints. We find that SOC sequestration is significantly increased in black soil cropland through practices such as non-inversion tillage, no-till, manure additions, biochar, biomass management, and the management practices that are needed to maintain SOC considerably by organic mulch, perennial crops, no-till strip tillage, soil and water conservation techniques. Besides SOC, there are large opportunities to increase chemical, physical and biological properties by cover crops, organic mulch, no-till, no-till strip tillage, manure additions, while still allowing increase in production of major cereals. Meanwhile, practices such as over crops, a crop-livestock farming system, and no-till showed good performance in mitigating climate change with reduction of greenhouse gases from soil. Fertilization is another story. With sustainable management, chemical and mineral fertilizer inputs in terms of macro and micro nutrition can provide sufficient nutrients for crop growth with resulting in good yields and limited environmental damage. In addition to cropland, grassland management practices such as grazing intensity and plant cover can reduce soil erosion and improve C sequestration, while different herbivores can improve soil C storage. To this end, meeting the global food security and sustainability challenges of the coming decades through black soils is possible, but will require considerable changes in sustainable crop system, nutrient, tillage, and water management.

In theory, black soils are suitable for most cropping systems such as rotation, perennial and organic with any crops in both small and large scale farmlands. A diverse cropping system in black soils can provide better ecological services that maintain and increase productivity and mitigate negative impacts.

By targeting measures that minimize soil threats, sustainable management practices in black soil areas

can address SOC loss, nutrient imbalance, biodiversity loss, compaction, and erosion. It is obviously those issues are fundamental to black soil protection especially in the aspect of crop production. However, it is difficult to find research and knowledge to address soil acidification, salinization and soil pollution. The reason could be that not all black soil areas are endangered by those soil threats. But, those three threats can damage black soil productivity and health in the longer term.

The future of black soil protection faces two great challenges: substantial increases in food demand must be met while mitigating soil threats. The sustainable use black soils with beneficial field practices and building suitable cropping systems are necessary strategies towards meeting these challenge, but they must be combined with efforts of awareness raising, education, extension and monitoring. Therefore it is vital that independent policies and agricultural development programmes must address all black soil threats through good practices and cropping system.

4.2 Relevant policies for the protection, conservation and/or sustainable management of black soils

In order to achieve the goal of protecting black soils, legislation at both global and national levels need to be developed and implemented, supported by a monitoring framework to track the dynamics and status of black soils. There are a number of national soil policies that are relevant to the management, protection and conservation of soils (Table 4.1) but very few are specific to black soils.

Given the importance of black soils for food security and nutrition, climate change mitigation and adaptation, and their value as a limited natural resource, there is a need to consider the following:

- The definition of “black soils” coined by the International Network of black soils should be widely used when referring to black soil legislation.
- A global agreement towards the sustainable management, conservation and protection of black soils is much needed.
- The degradation of black soils should be halted, particularly addressing the main soil threats: soil erosion, loss of soil organic carbon and soil sealing.
- A global programme to restore black soils should be established with the understanding that this is a limited natural resource.
- Capacity development needs to become an important instrument of a global technical cooperation programme between countries that have black soils.



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Table 4.1 Legislation, programmes and institutional constraints of the countries for the protection, conservation and/or sustainable management of black soils

Source: Author's elaboration and legal instructions of black soil countries in Annex 1

Country	Availability of specific legislation on black soils	Legislation and regulation related to black soils	Research and programmes at national level on soil protection	Policy and institutional constraints for the conservation of black soils
Canada	No	At present, black soil conservation policies are created and initiated at various levels of government. More specifically, soil conservation related legislative acts such as Alberta Soil Conservation Act (Government of Alberta, 2011) and other provincial government incentive programmes (Government of Manitoba, 2008; Government of Saskatchewan, 2020) were initiated.	Every five years, the Programme reports on the health of the Canadian agriculture and agrifood system for the last 30 years (1981 to 2011) where it is used to compare Canada's agri-environmental performance. Among many agri-environmental performance indicators, soil cover as reported by the soil cover indicator has shown dramatic improvements.	In 1984, a report titled "Soil at Risk – Canada's Eroding Future" by the Standing Senate Committee on Agriculture, Fisheries and Forestry was published but a lot has changed since then. Climate, environment, agriculture management, new crops and increased production demand have posed new challenges in soil (including black) conservation.
Mongolia	No	At present, there are over 8 legal laws relevant black soil protection implemented in crop area of Mongolia (e.g Law on Land of Mongolia, 2002; Law on Agriculture of Mongolia, 2016).	"Sustainable development concept of Mongolia-2030" is fundamental for the sustainable development of soil for food production and agriculture including black soil management.	No long-term policy strategies specific focus on improving soil fertility and reducing erosion.
Uruguay	No	The soil conservation law was updated in 2008 and effectively applied from 2013. The Uruguayan law is based on the principle that soil conservation is of general interest, over any particular interest.	The Soil Use and Management Plan (SUMP): i) precise geographic location, ii) description of the rotation to be made, iii) projected yields of the different crops, and pastures in the rotation, iv) dominant soil type in the polygon, and v) topographic characteristics defining length and slope (LS) in USLE/RUSLE.	Despite using no-till (NT), the new cropping intensification was made by abandoning the rotation with pastures, going back to continuous cropping. These changes resulted again in soil erosion problems.

Country	Availability of specific legislation on black soils	Legislation and regulation related to black soils	Research and programmes at national level on soil protection	Policy and institutional constraints for the conservation of black soils
Brazil	No	National legislation of soil conservation apply to black soils. In July 1975, the law on mandatory soil conservation planning and erosion control was approved (Brazil Government, 1975). In August 1981, the National Environment Policy, highlights the rational use of soil, subsoil, water and air, and includes soil conservation in the national policies (Brazil Government, 1981).	Any action for the usage and management of rural soils, including black soils, must be carried out through planning, based on the concept of land use capacity or agricultural suitability, requiring the application of conservation practices validated by official research institutions.	Instruments proposed for the use, management, recovery and conservation of soil and water should consider the current conditions, changes in land occupation, and their limitations or potential.
Thailand	No	There are two types of regulatory documents that are related to soil conservation: Land Development Act and Land Use Plan.	The Land Use Plan of Thailand 2019 was formulated in response to the strategic framework of Thailand's 20-year National Strategy, which covered land suitability analysis and land potentials evaluation.	Legislation is being set forth the whole country on agricultural land preservation; such a policy should be implemented with awareness.



Country	Availability of specific legislation on black soils	Legislation and regulation related to black soils	Research and programmes at national level on soil protection	Policy and institutional constraints for the conservation of black soils
China	One national law, two provincial legislations targeting black soil protection	<p>The 35th meeting of the Standing Committee of the 13th National People's Congress adopted the National Law of the Black Soil Protection on 24 June 2022. The law includes 34 regulations in terms of determining the scope of protection, assessment, monitoring, penalties, and ensure utilization as arable land; Jilin province has carried out the local legislation on the protection of black soils from 2016 including planning and evaluation, specific protection measures, supervision and management, legal liability, and bylaws, stipulation.</p> <p>Heilongjiang province enacted a local regulation on black soil protection in terms of use and planning, conservation and restoration, construction and utilization, monitoring and evaluation, supervision and management, legal liability.</p>	The Ministry of Agriculture and Rural Affairs (MARA) has recently launched a plan of action for conservation tillage in the black soil area, and released the "National Black Soil Protection Project Implementation Plan (2021–2025)".	More efforts should be focused on the protection scope clarification, the development of protection mechanism, establishment of protection system, and construction of a legal liability system.



Country	Availability of specific legislation on black soils	Legislation and regulation related to black soils	Research and programmes at national level on soil protection	Policy and institutional constraints for the conservation of black soils
Bulgaria	No	Legal instrument in Bulgaria towards protection of soils is the hierarchy of norms, the principle of intelligibility and accessibility of the law in force. The elements of the legislation are contained in the following normative acts: The Law on Soils, the Act for Protection of Agricultural Land, and the Environmental Protection Act.	The Rural Development Programme (Bulgaria Government, 2014), especially now in the second programming period 2013–2020, supports and financially stimulates (subsidies / compensatory payments) activities in agriculture and rural areas related to environmental protection – soils and waters, and EU Natura 2000 protected areas network zones.	The analysis of the existing legislation in Bulgaria regarding the assessment of the impact on the soils including black soils shows the lack of uniform procedure according to the criteria; from these facts it can be inferred that fragmentation has been observed.
Poland	No	The Act on the Protection of Agricultural and Forest Land (Poland Government, 2017) is aimed to protect mineral soils of high quality and all organic soils located on the agricultural land in Poland.	The contamination status of arable soils is monitored every 5 years since 1995 within the countrywide national Programme “Monitoring of the chemistry of arable soils” (Poland Government, 1995).	The black soils have no special evaluation criteria but like other arable soils have to fulfill the strict criteria stated in the regulation (Poland Government, 2016).
Türkiye	No	The purpose of the Law 5403 is to determine the principles and procedures that will ensure the protection and development of the soil resources including black soils and ensure their planned use in accordance with the environmental priorities and sustainable development principles (Türkiye, 2005).	In order to protect soils, two main mechanisms were adopted (Article 5, 6 and 12) as 1) the establishment of the “soil protection board (SPB)” in each province 2) Preparation of Soil Conservation Projects (SCP).	Need to strengthen the coordination between different governmental bodies and distributed structure of soil information were the main challenges to implement the Voluntary Guidelines on Sustainable Soil Management (VGSSM)

Country	Availability of specific legislation on black soils	Legislation and regulation related to black soils	Research and programmes at national level on soil protection	Policy and institutional constraints for the conservation of black soils
Russian Federation	No	The regulatory documents on black soil conservation can be grouped into three categories.1) Related to the sustainable management of black soils, there is one document, namely: The code of a conscientious land user and it is adopted in the Belgorod administrative region; 2) related to the SSM of agricultural lands; 3) related to the protection of fertile topsoil in the areas subjected to construction, mining, geologic survey and other types of activity that pollutes or destroys the topsoil.	The federal target Programme "Preservation and restoration of soil fertility of agricultural lands and agrolandscapes as a national treasure of Russian Federation started in February 20 2006.	Additional research is required for a clearer categorization of the excess of the content of heavy metals and toxic elements; Comparison of the indicators of the contaminated upper fertile layer with the background values is also used, but the selection of the background territory is an obstacle, since the indicators can be varied much from it.
Slovakia	No	Laws relevant to black soil protection in Slovakia include the Protection and Use of Agricultural Soil (Soil Protection Act), Water Act, the Act for the Application of Sewage Sludge, Land Consolidation Act, The Act on Environmental Impacts Assessment.	Soil Service within the Soil Science and Conservation Research Institute (SSCRI) is responsible for collecting data on the soil quality in Slovakia and ensures that the owners/tenants comply with the provisions of the Soil Protection Act.	Prescribe measures and activities should be easy to be understand that the owners or tenants of the land can undertake in order to rectify the situation.
Ukraine	No	The Land Code of Ukraine is the basic national regulatory document in the field of owning, use, and disposal of land (Ukraine, 2002). Article 150 of Land Code of Ukraine has established the special legal status of black soils. All kinds of black soils are considered "especially valuable land" (EVL).	According to of the Ukrainian Law "On land protection", agrochemical surveys are systematically carried out in agricultural land in order to control the dynamics of soil fertility. Initial and current levels of key soil indicators are recorded in the special agrochemical passport (Ukraine Government, 2003b).	Currently the large areas of black soils in Ukraine are heavily affected by war events leading to extensive contamination, compaction and degradation in general.

19 | National Implementation Plan for Black Soil Protection



Black soil monitoring, Nenjiang County of China.

Soil management is sustainable if the supporting, provisioning, regulating and cultural services provided by soil are maintained or enhanced without significantly impairing the soil functions that enable those services or biodiversity. Conservation tillage is a sustainable soil management (SSM) practice that uses crop straw mulching and no-till, which can effectively reduce wind and water erosion of soil, enhance soil fertility, increase moisture retention and drought resistance, and improve agro-ecological and economic benefits.

The Chinese Government plans to vigorously promote SSM practices in terms of conservation tillage and other technologies on black soils in the northeast region. The Ministry of Agriculture and Rural Affairs (MARA) launched a national action plan for conservation tillage in black soil areas in 2020, aiming to implement SSM on 7.3 million hectares in two years (MARA, 2020).

The MARA and relevant departments published the “National Implementation Plan for Black Soil Protection (2021–2025)” (MARA, 2021). The plan provides guidance for black soil protection and utilization in the next five years, specifying the target tasks of implementing 16.7 million hectares of black soils following the guidance, mitigating 25 000 erosion ditches and improving the quality of arable land by 2030.

20 | Black soil protection legislations



Black soil monitoring, Nenjiang County of China

The Black Soil Protection Law of the People's Republic of China, was enacted on August 1, 2022 (Xinhua News Agency, 2022; Lawinfochina, 2022). According to this law, black soils refers to arable land with a black or dark black humus topsoil layer with good properties and high fertility within the relevant areas of Heilongjiang, Jilin, and Liaoning provinces and Inner Mongolia Autonomous region. The agricultural and rural authorities of the State Council shall determine the scope of black soil protection taken into account the history of black soil reclamation and the currently status. The protection of black soils should be in a scientific and reasonable manner and adjusted in accordance with the principle most conducive to comprehensive protection, integrated management, and systematic restoration. This law specifies that China shall implement a scientific and effective policy for the protection of black soils. Financial investment in black land protection shall be guaranteed, and engineering, agronomic, agricultural and biological measures shall be taken to protect the productivity of black soils and maintain the total area of black soils. In addition, the law emphasizes that anyone who steals or indiscriminately digs or buys black soils shall be punished severely in accordance with the provisions of the relevant laws and regulations on soil management.

5. Conclusions and recommendations

5.1 Conclusions

This report constitutes a first attempt to compile and review the status of black soils based on the contributions of all the experts involved. This can be summarized in the following conclusions:

Black soils occupy 725 million hectares of the land surface and constitute 5.6 percent of global soils. They are primarily found in the Russian Federation (327 million hectares), Kazakhstan (108 million hectares), China (50 million hectares), Argentina (40 million hectares), Mongolia (39 million hectares), Ukraine (34 million hectares), and the United States of America (31 million hectares).

Black soils are a major reservoir of soil organic carbon (SOC): approximately 56 billion tonnes of carbon (Pg). The role of this reservoir on the carbon cycle and its importance in climate change (mitigation, adaptation and building resilience) are notable. They contain 8.2 percent of the world's SOC stocks and can provide 10 percent of the global total SOC sequestration potential, with Europe and Eurasia having the highest sequestration potential (over 65 percent of the total) and Latin America and the Caribbean around 10 percent. The maintenance of current carbon stocks in black soils and the realization of their potential carbon sequestration should constitute a priority for the global community.

Black soils are fundamental for providing food and nutrition for the global population and can be called the world's food basket. Although only approximately 17 percent of global cropland occurs on black soils, in 2010, 66 percent of sunflower seeds, 51 percent

of small millet, 42 percent of sugar beet, 30 percent of wheat and 26 percent of potatoes were harvested globally from black soils.

Because of their high suitability for agriculture (due to their natural fertility, high organic carbon content and very active soil biodiversity interactions), these soils are subject to intensive agriculture and, in many cases, are under unsustainable soil management practices. This is a major cause of concern as these soils are becoming degraded.

While approximately, 31 percent of global black soils are cultivated, but great portions of these soils remain with their natural land cover of forests (29 percent of black soils) and grasslands (37 percent of black soils). These non-cultivated black soils are found primarily in the Russian Federation and Canada. The protection of these uncultivated black soils should constitute a global priority because of the very high potential for carbon emissions to the atmosphere if these soils are converted to other land uses.

Overall the conservation and sustainable management of black soils should constitute a top priority not only for countries with black soils but for the world, as our food security greatly depends on these soils. A key first step is to develop a monitoring system to review progress of the status of and changes to the condition of black soils.

Table 5.1 below summarizes the status and challenges of the world's black soils in terms of sustainable management, protection and conservation, and policies.

Table 5.1 Summary of the status and challenges of the world's black soils

Source: Author's elaboration

Theme	Status and challenges
Sustainable use and management	<ul style="list-style-type: none">- Loss of SOC and erosion from cultivated black soils continues, leading to increasing greenhouse gas (GHG) emissions and the loss of their natural fertility.- Adoption of SSM practices by farmers remains limited due to lack of technical support, knowledge exchange, and provision of financial incentives and enabling environment.
	<ul style="list-style-type: none">- Black soils share similarities in management, although SSM practices should be tailored to local and specific edaphoclimatic and socioeconomic conditions.- Acidification, salinization and contamination of black soils have not been yet sufficiently investigated, without having significant findings.- Large areas of black soils are heavily threatened by various types of degradation and armed conflicts, which makes it difficult to implement policies for their sustainable use and management.
	<ul style="list-style-type: none">- Due to rapid urban sprawl, soil sealing is a constant threat for the protection and conservation of black soils.- The list of measures for the protection and conservation of black soils will differ at different scales (from local to global).
Protection and conservation	
Policies and enabling environment	<ul style="list-style-type: none">- Various national soil policies including the protection and sustainable management of soils, but only one of them (adopted by the Chinese Government) is specific for black soils.- Lack of an agreement for fostering the sustainable management of black soils (for conservation, protection and production).



5.2 Recommendations

Given the forward-looking vision of this report, the following recommendations should be considered by all stakeholders if we are to continuously benefit from the services provided by black soils.

Farmers:

- Maintain or even increase SOC stocks through proven SSM practices, such as no-till, manure addition, biochar, biomass management, organic mulch, perennial crops, no-till strip tillage, and soil and water conservation techniques, and to reduce GHG emissions through proven sustainable soil management practices, such as cover crops, crop-livestock farming system, and no-till.

Research/academia:

- Support the development of good practices (based on scientific evidence) for the sustainable management of black soils.
- Contribute with science to the refinement of the black soil definition and in the establishment of the monitoring system.

National governments:

- Foster the adoption of proven sustainable soil management practices by empowering farmers through national financial incentives to protect black soils.
- Promote the RECISOIL (Recarbonization of Global Soils) initiative in countries with black soils.
- Establish national programmes specifically including targeted research to manage and restore black soils.
- Support policies and mobilize domestic and international financial resources for the sustainable management, restoration and conservation of black soils.

International Network on Black Soils:

- Strengthen awareness raising campaigns on the importance of black soils as the most productive and threatened natural resource in the world.
- Refine the current definition of “black soils” and advocate for the establishment of a monitoring system of black soils under the International Network of Black Soils.
- Advocate for actions towards the the sustainable management, conservation, protection and production of global black soils.
- Strengthen technical cooperation among countries with black soils in order to enhance capacities for sustainably managing and monitoring black soils.



Annex A: legal instruments

A.1 Brazil

- **Soil protection and erosion combat plans and other measures**, adopted by the Ministry of Agriculture on 14 July 1975.
- **Provides for the National Environmental Policy, its purposes and mechanisms of formulation and application, and other provisions**, adopted by the Ministry of Agriculture on 31 August 1981.
- **National Water Resources Policy**, adopted by the Federal Constitution on 8 January 1997.
- **National Policy on Climate Change**, adopted by the National Congress on 29 December 2009.
- **Sectoral Plan for Mitigation and Adaptation to Climate Change for the Consolidation of a Low Carbon Economy on Agriculture: ABC Plan**, adopted by the Ministry of Agriculture, Livestock and Supply in 20121.
- **Provides for the Protection of Native Vegetation**, adopted by the National Congress on 25 May 2012b.
- **Combating Desertification and Mitigating the Effects of Drought and its instruments; foresees the creation of the National Commission to Combat Desertification; and takes other measures**, adopted by the National Congress on 30 July 2015.
- **Recovery of Native Vegetation**, adopted by the Federal Constitution on 23 January 2017.
- **Payment for Environmental Services**, adopted by the Federal Constitution on 13 January 2021.

A.2. Bulgaria

- **Revised European Charter for the Protection and Sustainable Management of Soil**, adopted by the Committee of Ministers of the Council of Europe on 17 July 2003.
- **Thematic Strategy for Soil Protection**, adopted by the Committee of Ministers of the Council of Europe on 22 September 2006.
- **Framework for the Protection of Soil and Amending Directive**, adopted by the Committee of Ministers of the Council of Europe on 22 September 2006.
- **Financing, Management and Monitoring of the Common Agricultural Policy and Repealing**

Council Regulations, adopted by the Committee of Ministers of the Council of Europe on 17 December 2013.

- **The Protection of Waters Against Pollution Caused by Nitrates from Agricultural Sources**, adopted by the Committee of Ministers of the Council of Europe on 12 December 1991.
- **Framework for Community Action to Achieve the Sustainable Use of Pesticides**, adopted by the Committee of Ministers of the Council of Europe on 21 October 2009.
- **Good Agricultural and Environmental Conditions**, adopted by the Committee of Ministers of the Council of Europe on 14 April 2015.
- **Waste and Repealing Certain Directives**, adopted by the Committee of Ministers of the Council of Europe on 19 November 2008.
- **Protection of the Environment, and in particular of the soil, when sewage sludge is used in agriculture**, adopted by the Committee of Ministers of the Council of Europe on 12 June 1986.
- **Assessment and Management of Flood Risk**, adopted by the Committee of Ministers of the Council of Europe on 23 October 2007.
- **Public Access to Environmental Information and repealing Council Directive**, adopted by the Committee of Ministers of the Council of Europe on 28 January 2003.
- **Environmental Liability with Regard to Prevention and Remedying of Environmental Damage**, adopted by the Committee of Ministers of the Council of Europe on 21 April 2004.
- **Assessment of the Effects of Certain Public and Private Projects on the Environment**, adopted by the Committee of Ministers of the Council of Europe on 16 April 2014.
- **Assessment of the Effects of Certain Plans and Programs on the Environment**, adopted by the Committee of Ministers of the Council of Europe on 27 June 2001.
- **Establishing an Infrastructure for Spatial Information in the European Community (INSPIRE)**, adopted by the Committee of Ministers of the Council of Europe on 14 March 2007.
- **Industrial Emissions (Integrated Pollution Prevention and Control)**, adopted by the Committee of Ministers of the Council of Europe on 24 November 2010.

- **Regions, Roadmap to a Resource Efficient Europe**, adopted by the Committee of Ministers of the Council of Europe on 20 September 2011.
 - **General Union Environment Action Programme to 2020 ‘Living Well, Within The Limits Of Our Planet’**, adopted by the Committee of Ministers of the Council of Europe on 20 November 2013.
 - **The Law on Soils**, adopted by the Government of Bulgarian on 6 November 2007.
 - **The Act for Protection of Agricultural Lands**, adopted by the Government of Bulgarian on 18 September 2018.
 - **The Environmental Protection Act (EPA)**, adopted by the Government of Bulgarian on 3 May 2019.
 - **Ordinance N° 4 on Soil Monitoring**, adopted by the Government of Bulgarian on 1 July 2004.
 - **The Law on Responsibility for Prevention and Elimination of Environmental Damages**, adopted by the Government of Bulgarian on 18 July 2017.
 - **The Act on the Ownership and Use of Agricultural Lands – Law on Land Acquisition**, adopted by the Government of Bulgarian on 1 March 1991. It was ratified on 18 July 2017)
 - **Ordinance N° 3 on the Norms for Permissible Content of Harmful Substances in Soils**, adopted by the Government of Bulgarian on 5 February 2010.
 - **Ordinance N° 4 on Soil Monitoring**, adopted by the Government of Bulgarian on 13 March 2009.
 - **Ordinance N° 26 on Reclamation of Disturbed Terrains, Improvement of Low-productive Lands, Removal and Utilization of the Humus Layer**, adopted by the Government of Bulgarian on 22 October 1996. It was ratified on 22 March 2002.
 - **Ordinance N° 30 on the Inventory and Surveys of Areas with Contaminated Soil, the Necessary Restoration Measures, as well as the Maintenance of the Implemented Restoration Measures**, adopted by the Government of Bulgarian on 16 February 2007. It was ratified on 17 October 2007.
 - **Ordinance N° 2 of 13.09.2007 on Protection of Waters from Pollution with Nitrates from Agricultural Source**, adopted by the Government of Bulgarian on 11 March 2008. It was ratified on 9 December 2011.
 - **The Rural Development Program**, adopted by the Government of Bulgarian in 2013.
 - **Updated National Program of Action for Sustainable Land Management and Combating Desertification (2014–2020)**, adopted by the Government of Bulgarian on June 2014.
 - **National Development Program: Bulgaria 2020**, adopted by the Government of Bulgarian in 2020.
 - **Strategy for Sustainable Agriculture Development in Bulgaria for the New Programming Period (2021–2027)**, adopted by the Government of Bulgarian in 2020.
 - **Program of Measures for Limitation and Prevention of Nitrate Pollution from Agricultural Sources in Vulnerable Areas**, adopted by the Government of Bulgarian on 5 May 2016.
 - **National Program for Prevention and Limitation of Landslides on the Territory of the Republic of Bulgaria, Erosion and Abrasion along the Danube and Black Sea Coast (2015–2020)**, adopted by the Government of Bulgarian in June 2015.
 - **Flood Risk Management Plans (2016–2021) and River Basin Management Plans (2016–2021)**, adopted by the Government of Bulgarian in 2015.
 - **National Strategy for Sustainable Development of Agriculture in Bulgaria (2014–2020)**, adopted by the Government of Bulgarian on March 2013.
 - **Updated National Action Plan for Management of Persistent Organic Pollutants (POPs) in Bulgaria (2012–2020)**, adopted by the Government of Bulgarian in 2011.
 - **National Program for Protection, Sustainable Use and Restoration of Soil Functions (2019 – 2028)**, adopted by the Government of Bulgarian on 3 November 2019.
- A.3. Canada**
- **Beneficial Environmental Practices for Crop Producers in Alberta**, adopted by the Alberta Agriculture, Food and Rural Development on 19 November 2020.
 - **Soil Conservation Act**, adopted by the Government of Alberta on 19 November 2020
 - **Soil Management Guide. Agriculture, Food and Rural Initiatives**, adopted by Government of Manitoba on 2008.
 - **Soils, Fertility and Nutrients**, adopted by the Government of Saskatchewan on 19 November 2020.

A.4. China

- **National Law of the Black Soil Protection**, adopted by the 35th meeting of the Standing Committee of the 13th National People's Congress, was enacted on 1 August, 2022.
- **northeast Black Soil Protection Planning Outline**, adopted by the Ministry of Agriculture and Rural Affairs, People's Republic of China, 12 July 2019.
- **the northeast Black Soil Conservation Tillage Action Plan**, adopted by the Ministry of Agriculture and Rural Affairs, 25 February 2020.
- **National Black Soil Protection Project Implementation Plan (2021–2025)**, adopted by the Ministry of Agriculture and Rural Affairs, 24 August 2021.
- **Regulations on the Protection of Arable Land of Heilongjiang province**, adopted by the People's Government of Heilongjiang province, 21 April 2016.
- **Interpretation of “Regulations on the Protection of Black Land in Jilin province”**, adopted by the People's Government of Jilin province 5 May 2021.
- **Regulation to Protect the Quality of Arable Land**, adopted by the People's Government of Liaoning province, 1 February 2006.
- **Regulation on the Maintenance of Arable Land**, adopted by the People's Government of Inner Mongolia, 27 December 1998.

A.5. Mongolia

- **Law on Land of Mongolia**, adopted by the Government of Mongolia in 2002.
- **Law on Agriculture of Mongolia**, adopted by the Government of Mongolia in 2016.

A.6. Poland

- **Act on the Protection of Agricultural and Forest Land**, adopted by the Government of Poland on 3 February 1995.
- **The Method of Assessing the Pollution of the Land Surface**, adopted by the Regulation of the Minister of Environment on 1 September 2016.
- **Monitoring of the Chemistry of Polish Arable Soils**, adopted by the Government of Poland in 2015.

A.7. Russian Federation

- **The Code of a Conscientious Land User**, adopted by the Government of the Russian Federation on 26 January 2015.

- **The State Regulation on the Fertility of Agricultural Lands, the Scale of the Regulation: National**, adopted by the Government of the Russian Federation on 30 December 2021.
- **The titles of regulatory documents: The Method of Calculation of the Soil Fertility Indicator in the Administrative Region of the Russia Federation**, adopted by the Government of the Russian Federation on 7 June 2017.
- **On Approval of the Procedure for State Monitoring of Agricultural Lands**, adopted by the Government of the Russian Federation on 24 December 2015.
- **On Approval of the Procedure for State Registration of Indicators of the State of Fertility of Agricultural Lands**, adopted by the Government of the Russian Federation on 4 May 2010.
- **Land Code of the Russian Federation (article #42)**, adopted by the Government of the Russian Federation on 25 October 2001. It was ratified 16 February 2022.
- **The Scale of the Regulation: National, 2001**, adopted by the Government of the Russian Federation on 25 October 2001. It was ratified 1 March 2022.
- **On Approval of Criteria for a Significant Decrease in the Fertility of Agricultural Land**, adopted by the Government of the Russian Federation on 22 July 2011.
- **Code of Administrative Offenses (article #8.6 “Deterioration and Destruction of Soil”, items #1 and #2)**, adopted by the Government of the Russian Federation in 2014.
- **Code of Administrative Offenses (article #8.7 “Failure to Comply with Obligations for Land Reclamation, Mandatory Measures for Land Improvement and Soil Protection”, items #1 and #2)**, adopted by the Government of the Russian Federation on 30 December 2001. It was ratified 1 March 2022.
- **Federal Law of 10.01.2002 N 7-FZ “On Environmental Protection (article #77)**, adopted by the Government of the Russian Federation on 10 January 2002. It was ratified 30 December 2021.
- **Methodology for Calculating the Amount of Damage Caused to Soils as an Object of Environmental Protection**, adopted by the Government of the Russian Federation on 8 July 2010. It was ratified 18 November 2021.

A.8. Slovakia

- **Act no. 220/2004a Coll. Act on the Protection and Use of Agricultural Land and on the Amendment of Act No. 245/2003 Coll. on integrated pollution prevention and control**, adopted by the Government of Slovakia on 28 April 2004.
- **Act no. 188/2003 Coll. on the Application of Sewage Sludge and Bottom Sediments to the Soil and on the amendment of Act no. 223/2001 Coll. on waste and on the amendment of certain laws as amended**, adopted by the Government of Slovakia on 6 April 2003
- **Act on Fertilizers 136/2000 Coll. and amendment to Act no. 394/2015 Coll.**, adopted by the Government of Slovakia on 21 April 2000
- **The Act 330/1991 Coll. on Land Consolidation, Land Ownership Arrangements, Land Offices, Land Fund and Land Associations**, adopted by the Government of Slovakia on 12 July 1991.
- **Act no. 24/2006 Coll. Act on Environmental Impact Assessment and on Amendments to Certain Acts**, adopted by the Government of Slovakia on 20 January 2006.
- **Land Value for Land Consolidation**, adopted by the Government of Slovakia on 27 October 2020.
- **Protected Agricultural Soils**, adopted by the Government of Slovakia on 27 October 2020.
- **Thickness of the Humus Horizon**, adopted by the Government of Slovakia on 27 October 2020.
- **Application of Sewage Sludge and Bottom Sediments**, adopted by the Government of Slovakia in October 2020.
- **Nitrate Directive**, adopted by the Government of Slovakia on 27 October 2020.

A.9. Thailand

- **Land Development Act B.E.**, adopted by the Government of Thailand on 1 November 2020. [Cited 1 November 2020].

A.10. Türkiye

- **Soil Protection and Land Use Law**, adopted by the Government of Poland on 19 May 2005.
- **Regulation for Protecting, Use and Planning of Agricultural Lands**, adopted by the Government of Poland on 9 November 2017.

A.11. Uruguay

- **Use and Conservation of Soils and Surface Waters Intended for Agricultural**, adopted by the Government of Uruguay on 23 December 1981.
- **Regulation of Uses, Conservation of Soils, and Surface Waters**, adopted by the Government of Uruguay on 16 September 2004. It was ratified 16 September 2008.
- **Regulation of the Use and Management of Water and Soil. Penalties for Non-compliance**, adopted by the Government of Uruguay on 11 September 2009.
- **Manual of Measures Required for Crops: Instructions for the Preparation and Presentation of Plans for the Responsible Use and Management of Soils**, adopted by the Government of Uruguay on 18 March 2013
- **Manual of Required Measures for Crops**, adopted by the Government of Uruguay in 2008.
- **National Budget of Salaries Expenses and Investment. Financial Year 2015-2019**, adopted by the Government of Uruguay on 19 December 2015.
- **The Regulation on the Presentation of Plans for the Responsible Use and Management of Soils**, adopted by the Government of Uruguay on 14 November 2018.

A.12. Ukraine

- **Land Code of Ukraine**, adopted by the Government of Ukraine on 1 January 2002.
- **State Committee of Ukraine on Land Recourses**, adopted by the Government of Ukraine on 6 October 2003.
- **On Amendments to the Legislative Acts of Ukraine about the Improvement of the Responsibility for the Self Employment of Land Plots**, adopted by the Government of Ukraine on 13 April 2012.
- **On land Protection**, adopted by the Government of Ukraine on 19 June 2003.
- **Procedure of Land Conservation**, adopted by the Ministry of Agricultural Policy and Food of Ukraine on 26 April 2013.



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