FIELD GUIDE

VISUAL SOIL ASSESSMENT

part 2

Maize

Visual indicators of environmental performance under cropping

A GUIDE

BioAgriNomics

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VISUAL SOIL ASSESSMENT

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Visual indicators of environmental performance under cropping

A GUIDE

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ASC	Anion storage capacity
ATP	Adenosine triphosphate
B	Boron
C	Carbon
Ca	Calcium
Ca^{2+}	Calcium cation
CEC	Cation exchange capacity
CH_4	Methane
CO_2	Carbon dioxide
qCO_2	Metabolic quotient
Co	Cobalt
Cu	Copper
Fe	Iron
FeS	Ferrous sulphide
Fe^{3+}	Ferric iron
Fe^{2+}	Ferrous iron
GHG	Greenhouse Gas
H_2S	Hydrogen sulphide
K	Potassium
K^+	Potassium cation
Mg	Magnesium
Mg^{2+}	Magnesium cation
Mn	Manganese
Mn^{3+}	Manganic ions
Mn^{2+}	Manganous ions
Mo	Molybdenum
N	Nitrogen
N_2	Nitrogen gas
NO_3^-	Nitrate
NO_3^--N	Nitrate-nitrogen
NO_2^-	Nitrite
N_2O	Nitrous oxide
Na	Sodium
Na^+	Sodium cation
NH_3	Ammonia
NH_4^+	Ammonium
O_2	Oxygen
P	Phosphorus
PO_4^{3-}	Phosphate
pH	Concentration of H^+ ions (Soil acidity/alkalinity)
RSG	Restricted spring growth
S	Sulphur
SO_4^{2-}-S	Sulphate-sulphur
SO_4^{2-}	Sulphate
SO_3^{2-}	Sulphide
VS	Visual score
VSA	Visual Soil Assessment
WFPS	Water-filled pore space
Zn	Zinc
ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER CROPPING
A GUIDE

Courtesy of Pioneer® brand products

1. Potential for nutrient loss into the groundwater and waterways

2. Carbon sequestration

3. Green house gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways

Assessment

1. To assess the susceptibility of soils under crops to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 71), the visual scores (VS) for Textural group, Soil colour, Soil smell, and Potential rooting depth from the Soil Scorecard, and the visual score (VS) for Root development from the Plant Scorecard. Also add a ranking score for the amount and solubility of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.

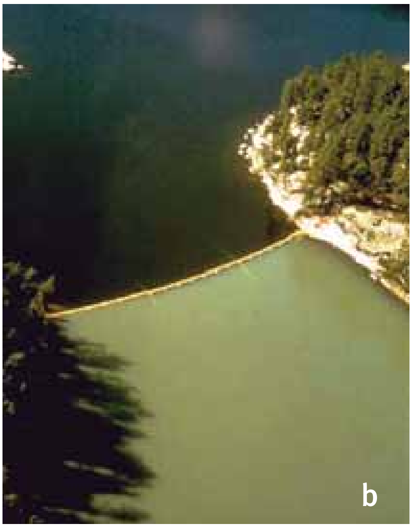
Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals[1], have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is greater than 7:1, P is limiting growth. If the N:P is less than 7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

[1] Non-crystalline iron and aluminium hydrous oxides and amorphous alumino-silicate clay minerals such as ferrihydrite and allophone.

PLATE 48 **Nutrient loss into waterways**



a) A field with a moderate potential for nutrient loss into the groundwater and lake. While it has a coarse loamy textural group and moderately good structure with a moderately rapid permeability, it has moderately high carbon levels and CEC in the topsoil, good potential rooting depth, good root development, and received moderate amounts of water-soluble fertiliser and nitrogen.

b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly assessed from five of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^--N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain more clay and generally more humus as well. Hence their CECs are higher and more able to adsorb and retain positively charged nutrients such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, NH_4^{+}, etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic* silty clay, *peaty* silt loam) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P can also readily leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root development** (p. 46) – Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with crops with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root development and the potential rooting depth.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light, well-structured soils, particularly when applied in large amounts. High rates of fertiliser are also applied to crops in an attempt to overcome sparse root systems and maximise yield. The over-use of highly soluble granulated N products readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^-. Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching. Nitrate and H^+ ions are produced following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should always be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes. In contrast to urea and other highly soluble fertiliser products, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of high analysis, highly soluble forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can have a negative affect on soil life. The microbial biomass and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–65 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^--N) from soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+-N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reduction in white clover. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical cropping practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Any one of the above indicators provides an estimate of the susceptibility of the soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 20, certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 20 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching into the environment. Crops are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth.

FIGURE 5 **Scorecard – visual indicators to assess the potential for nutrient loss**

Landowner:

Land use:

Site location:

GPS ref:

Sample depth:

Topsoil depth:

Soil type:

Soil classification:

Drainage class:

Date:

Textural group (upper 1 m): ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey ☐ Other

Visual indicators of nutrient loss		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below[1])	pg. 2		x 3	
Soil structure (Scoring protocol is given below[2])	pg. 4		x 2	
Potential rooting depth (mm)	pg. 22		x 3	
Root development	pg. 46		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below[3])			x 3	
NUTRIENT LOSS INDEX (sum of VS rankings)				

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 11
Moderate potential for nutrient loss	11–20
Low potential for nutrient loss	> 20

1 **Textural group** (Figure 2b, p. 3):
VS = 2 for Clayey; **VS = 1.5** for Fine silty; **VS = 1.0** for Fine loamy; **VS = 0.5** for Coarse silty; **VS = 0** for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 rispectively to the VS score. Note VS scores cannot exceed a value of 2.

2 **Soil structure – Is the land most susceptible to a) leaching, or b) runoff?**
a) Land susceptible to leaching – Flat land with little or no runoff (overland flow)
VS = 2 for Poor soil structure; **VS = 1.5** for Moderately poor soil structure; **VS = 1.0** for Moderate soil structure; **VS = 0.5** for Moderately good soil structure; **VS = 0** for Good soil structure.
b) Land susceptible to runoff – Gently undulating to rolling land
VS = 2 for good soil structure; **VS = 1.5** for Moderately good soil structure; **VS = 1.0** for Moderate soil structure; **VS = 0.5** for Moderately poor soil structure; **VS = 0** for Poor soil structure

3 **Amount and form of fertiliser and N applied**
VS = 2 if using liquid foliar sprays or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 80 kg N/ha/yr are applied; **VS = 1.0** if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 160–240 kg N/ha/yr, using highly soluble, salt-based and nitrogenous fertilisers; **VS = 0** if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 320 kg N/ha/yr are applied.

2. Visual indicators to assess the potential for carbon sequestration

Assessment

1. Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 8, p. 79) the visual scores (VS) for Soil texture, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root development and Crop yield from the Plant Scorecard. Add also a ranking score for the clay mineralogy, the amount and form of fertiliser and nitrogen applied per annum, and for the method of cultivation (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.

Importance

THE AMOUNT OF C in a soil = C inputs – decomposition rates. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition, leaching and volatilization (Plate 49). A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than the decomposition rates (Plate 50). Farmers can reduce their ecological and carbon footprint and 'grow' their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture's contribution to greenhouse gas emissions, providing a cost- effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, two indicators of plant performance, and from the method of cultivation and the amount and form of fertilisers and nitrogen used, as described below. Crops such as maize silage where most of the plant is removed are C negative.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of organic C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are < 2 μm and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

PLATE 49 **A carbon positive field**

Photo: Courtesy of Baker No-Tillage Ltd

A carbon positive field using no-till technology to sow directly into maize residue left on the surface. The field has good soil colour compared with the fenceline, good root development, potential rooting depth, and crop yields, moderate earthworm numbers, and 80 kg N/ha/yr are applied in a carbon-friendly form.

PLATE 50 **A carbon negative field**

A carbon negative field under continuous conventional cultivation. The field has moderately poor soil colour compared with the fenceline, poor earthworm numbers, moderate potential rooting depth, root development, and crop yields, and 200 kg N/ha/yr are applied in a non-carbon friendly form. Total organic C in the upper 200 mm of soil declined from 90.8 tonnes/ha under permanent pasture to 41.2 tonnes/ha after 35 yrs of continuous conventional cultivation (Figure 6, p. 77).

Clay mineralogy (see scorecard, p. 79) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and alumino-silicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle-size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under 20 yrs continuous barley contain about 229 t C/ha in the top 1m, of which 159 t C/ha (69 percent) occurs in the upper 300 mm, and 70 t C/ha (31 percent) between 300 and 1000 mm. Compare this with non-allophanic soils below. The amount of C in the upper 300 mm of allophanic soils under cropping is only 4 t/ha less than under permanent pasture, illustrating its relative stability despite continuous, long-term conventional cultivation.

Soil colour compared with that under the fenceline (p. 10) can provide a good indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present. With the exception of poorly aerated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C (Fig. 10, p. 86).

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. The number and activity of soil microbes at depth is much less than in the topsoil and so the carbon is more protected and able to build up because it is less likely to be mineralised. Deep burrowing earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil C.

Potential rooting depth (p. 22) and the **Root development** (p. 46) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 128 tonnes C/ha after 23 yrs cereal and maize cropping: 85 t C/ha (67 percent) occur in the upper 300 mm, and 42 t C/ha (33 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good potential rooting depth of 1 m contain about 134 t C/ha after 22 yrs maize cropping, of which 64 t C/ha (48 percent) occur in the upper 300 mm, and 70 t C/ha (52 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme. Note the significantly lower C levels of these soils under conventional cultivation compared with pasture (Fig. 6, p. 77).

Crop yield (p. 58) can provide a further indication whether soil C is increasing, decreasing or at steady state. The greater the crop yield, the greater the root and shoot mass, and therefore the greater the input of C from the root system and the decomposition of the additional surface litter and surface residue. A 14-tonne/ha crop of maize for grain would produce an above-ground C input from the surface litter and residue of approximately 7 t C /ha, and a below-ground C input of 2 t/ha from the roots, a total of 9 t C/ha. An 11- tonne/ha crop of maize adds a total of approximately 7.1 t C/ha to the soil, or 21 percent less than the higher producing crop. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the crop has good root development and potential rooting depth, and the soil is allophanic with a good earthworm population, and doesn't receive high applications of soluble, salt-based nitrogenous products. The application of high rates of granular N to boost yield, promotes the vegetative growth of the shoots relative to the roots. The over-use of N also creates lazy plants, encouraging a shallow root system and therefore less C input. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil. In addition, the microbial decomposition of roots, plant litter and husks produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil. The input of C in the soil from maize for silage is considerably less than maize for grain because much of the above ground vegetative matter is removed at harvest. Maize silage can therefore have a C negative effect.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture and temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing crop growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Amount and form of fertiliser and nitrogen applied to cropping soils (see scorecard, p. 79) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, compost teas, animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and crop management, good crop yields and C levels can be sustained and increased over the long term. The form in which essential elements are applied can also have an effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and is the preferred form for improving crop quality, and if the seedlings or crop are sensitive to chlorine.

Similarly, while nitrogen promotes crop growth and therefore the input of C into the soil, certain forms of N are more effective than others at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic carbon and carbohydrate such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N. The excessive use of soluble granular forms of N and high analysis nitrogenous fertilisers also cause the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 10:1–100:1. The oversupply of N stimulates bacteria to mineralise 2–3 times the amount of humus they would ordinarily mineralise. Moreover, the high use of granular forms of N such as urea, reduce the earthworm and microbial biomass, further reducing C levels in the soil.

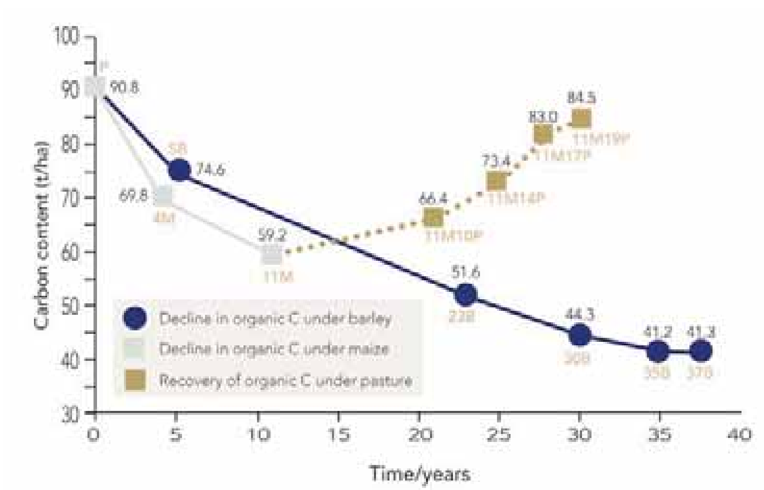
The plant converts CO_2 in the atmosphere into sugar (carbon) by photosynthesis in the leaves of the plant. The sugar dissolves as liquid glucose in the sap of the plant and is subsequently transferred to the soil through the roots to feed the soil microbes. The microbes in turn bring trace elements to the plant in exchange for the sugar. This process of C transfer from the plant to the soil, and the rate of photosynthesis, is disrupted by the over-use of high analysis, highly soluble forms of N and P. These include urea and anhydrous ammonia, and di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (e.g., humates), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70 percent). The utilization of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root development, and crop yield.

The addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

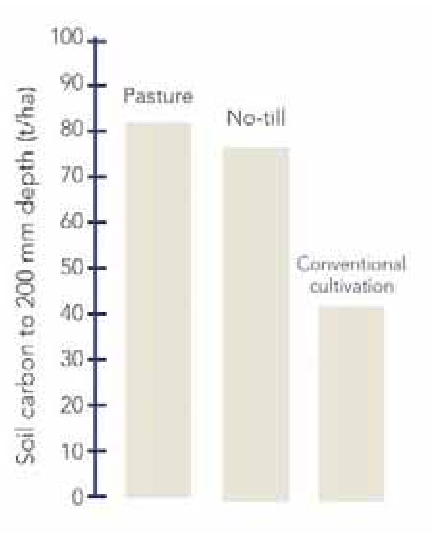
The **method of cultivation** (see scorecard, p. 79) can have a significant effect on soil C levels. Soil organic C can decline markedly under continuous conventional cultivation because the high level of soil disturbance aerates the soil, increasing the rate of mineralisation of soil organic C by microbial respiration and its oxidation to CO_2. The rate of C loss is particularly rapid in the first 4–5 years of cropping, followed by a slower rate of decline, eventually reaching an equilibrium where only the more stable and physically protected carbon remains in the soil (Fig. 6). Total soil C is seen in Fig. 6 to decline by 31.6 t/ha in the upper 200 mm of soil after 11 yrs continuous maize, and by 49.6 t/ha after 35 yrs continuous barley; an average loss of 2.9 and 1.7 t/ha/yr respectively. Note the initial slow rate of recovery of total C after 10 years of pasture following 11 yrs of maize. After 19 yrs of ryegrass/clover pasture, the total C had not recovered to pre-cropping pasture levels of 90.8 t/ha. The significant loss of C under both maize and barley, and the slow rate of C recovery under pasture are due in part to the poor management practices that prevailed. The slow rate of recovery of C under pasture was also due to the extremely compacted, poorly aerated state of the soil.

FIGURE 6 **Total C in the topsoil under pasture and continuous cropping**



Total C in the topsoil (0–200 mm) after 11 yrs and 37 yrs of continuous maize and barley respectively under conventional cultivation.
Note the rate of recovery of total C after 10, 14, 17 and 19 years of pasture following 11 yrs of maize.

FIGURE 7 **Total C in the topsoil under pasture, no-till and conventional cultivation**



Courtesy of Craig Ross

Total C in the topsoil under pasture, 20 yrs of double cropping (with a winter brassica and cereal crop) using no-till, and 35 yrs of conventional cultivation.

In comparison, the loss of soil C under no-tillage is significantly less than under conventional cultivation (Fig. 7). In some instances, C levels have increased in the upper 150 mm of soil under no-tillage compared with pasture. The greatest increases in soil C can occur at a depth of 300–600 mm under 'pasture cropping' practices where no herbicides or insecticides have been applied. The substantial loss of C under conventional cultivation and the slow rate of C recovery under pasture are due to the non-adoption of carbon capture and storage (CCS) management practices.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore 'grow' the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 32), certain management practices and specific types of fertiliser need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 32) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits.

FIGURE 8 Scorecard – visual indicators to assess the potential for carbon sequestration

Landowner:	**Land use:**
Site location:	**GPS ref:**
Sample depth:	**Topsoil depth:**
Soil type:	**Soil classification:**
Drainage class:	**Date:**

Textual group (upper 1 m): ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey ☐ Other

Visual indicators of soil carbon		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below[1])	g. 2		x 2	
Clay mineralogy (Scoring protocol is given below[2])			x 2	
Soil colour	g. 10		x 2	
Earthworms (Number =) (Av. size =)	g. 14		x 3	
Potential rooting depth (mm)	g. 22		x 3	
Root development	g. 46		x 3	
Crop yield	g. 58		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below[3])			x 2	
Method of cultivation (Scoring protocol is given below[4])			x 3	
SOIL CARBON INDEX (sum of VS rankings)				

Soil Carbon Assessment	Soil Carbon Index
Potentially poor carbon levels	< 17
Potentially moderate carbon levels	17–32
Potentially good carbon levels	> 32

1 **Textural group: VS = 2** for Clayey; **VS = 1.5** for Fine loamy and Fine silty; **VS = 1.0** for Coarse silty; **VS = 0.5** for Coarse loamy; **VS = 0** for Sandy.

2 **Clay mineralogy: VS = 2** if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; **VS = 1** if the soil has moderate levels of Fe & Al hydroxides and amorphous alumino-silica clay minerals with an ASC of 60–75 percent; **VS = 0** if the soil has little or no Fe & Al hydroxides and amorphous alumino-silica minerals; ASC is < 45 percent.

3 **Amount and form of fertiliser and N applied: VS = 2** if "smart" fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; **VS = 1** if 120–160 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; **VS = 0** if ≥ 200 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based N fertilisers.

4 **Method of cultivation: VS = 2** if using 'pasture cropping' and no-till practices; **VS = 1.5** if using strip tillage; **VS = 1** if using minimum tillage; **VS = 0.5** if using a mouldboard plough with limited secondary cultivation; **VS = 0** if using continuous mouldboard ploughing with intensive secondary cultivation.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

GHG emissions

3. Visual indicators of potential greenhouse gas emissions

Assessment

1. Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 12, p. 89) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual score for Crop yield from the Plant Scorecard. Also add a ranking score for the method of cultivation used and the amount and form of N applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.

Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C; without them the earth's average temperature would be around –18°C. However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Agriculture can provide a significant source of CH_4 and N_2O and is responsible for 15 percent of worldwide greenhouse gas emissions. CO_2 is emitted under arable cropping, however it is reabsorbed as photosynthate by the crop and is therefore greenhouse neutral. While high emission levels of GHGs are more to do with the way we farm, climate friendly and smart agricultural management can significantly reduce emissions.

GHG emissions from cropping result from a number of sources, including the soil, the burning of fossil fuels by farm machinery, and the production and application of nitrogenous fertilisers. The level of emissions varies according to a number of factors, including the condition of the soil, the method of cultivation, and the amount and form of fertiliser N applied, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO_2 to soil C, and by promoting the soil as a CH_4 sink. The C credits gained can help off-set their GHG emissions.

PLATE 51 **Field with a low potential for greenhouse gas emission**

Field with a low potential to emit GHGs due to the soil being a well-drained, coarse loamy soil with good porosity under a no-tillage regime. In addition, good crop growth and yield remove a large amount of CO_2 from the atmosphere and CO_2 escaping from the soil by photosynthesis.

PLATE 52 **Field with a high potential for greenhouse gas emission**

Field with a high potential to emit GHGs due to the soil being an imperfectly to poorly drained, clayey soil with poor porosity under continuous conventional cultivation. In addition, poor crop growth and yield remove only small amounts of CO_2 from the atmosphere and CO_2 escaping from the soil by photosynthesis.

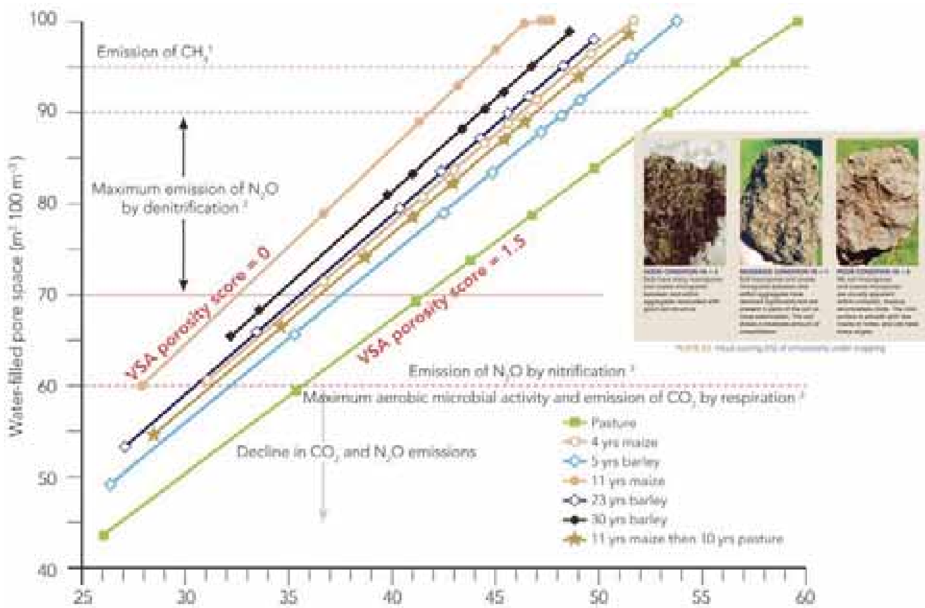
The potential of a site to emit GHGs can be roughly assessed from four indicators of soil quality, one indicator of plant performance, the amount and form of nitrogen applied, and the method of cultivation, as described below.

Soil textures (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major 'driver' of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs.

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O, and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 9); emissions of N_2O are lowest when the WFPS is < 50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 9) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O. In contrast, a severely compacted soil after 11 yrs of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 9) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2. While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is

FIGURE 9 **Affect of water-filled pore space and water content on greenhouse gas emissions**



[1] After MacDonald *et al.* (1996); [2] After Dobbie *et al.* (1999); [3] After Linn and Doran (1984)

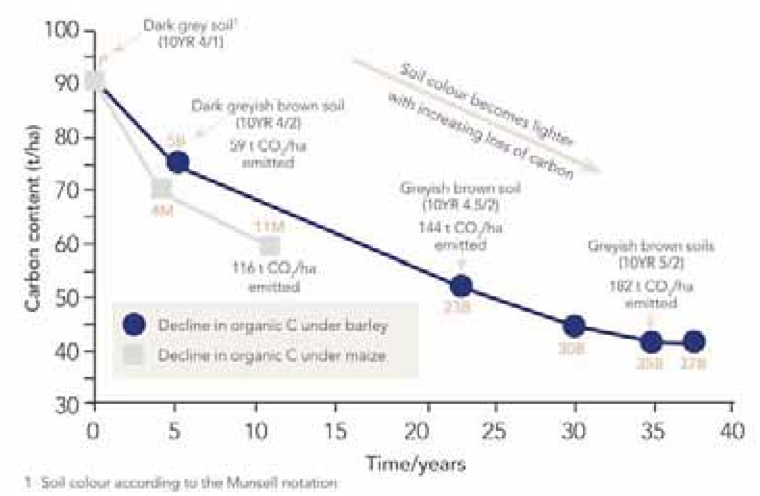
Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

hence an effective means of reducing GHG emissions. The relationship between the WFPS and the visual assessment of the porosity of the soil, as shown in Fig. 9, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink. A lighter soil colour compared with soil under the fenceline can also indicate the loss of soil C and the emission of significant amounts of CO_2 into the atmosphere (Figure 10).

GHG emissions

FIGURE 10 **Soil C loss and associated CO_2 emissions under continuous cropping**



Soil C loss, associated soil colour, and CO_2 emissions under continuous maize and barley cropping using conventional cultivation.

Crop yields (p. 58) can provide an indication of the potential to reduce GHG emissions. The greater the crop yield, the greater the amount of CO_2 removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO_2 emitted by microbial respiration, the emission of GHGs from the consumption of the crop by stock, the burning of fossil fuels by farm machinery, and the application of nitrogenous fertilisers. As CO_2 escapes from the soil, most, if not or all, is absorbed by the stomata on the crop leaves, which have an insatiable appetite for CO_2. The greater the canopy cover (leaf area index) and the quicker the canopy closure, the greater the amount of CO_2 removed. Furthermore, if we assume that one kilogram of carbon in a maize crop removes 3.67 kg CO_2 from the atmosphere, a field growing 25 tonnes of maize silage/ha (or 10.3 t C/ha) will remove approximately 38 tonnes of atmospheric CO_2/ha. A field growing just 20 tonnes of maize silage/ha (or 8.2 t C/ha) will remove 30 tonnes of atmospheric CO_2/ha, 22 percent less than the higher producing field. While CO_2 is the least potent of the GHGs with a Global Warming Potential that is 21 and 310 times less than CH_4 and N_2O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO_2 into sugars and oxygen, and subsequently into soil C, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Poor crop yield and the associated reduced crop cover would also reduce insulation from the sun, thereby increasing soil temperatures and reducing the uptake of available N and plant-available water, stimulating N_2O emissions by microbial nitrification and denitrification.

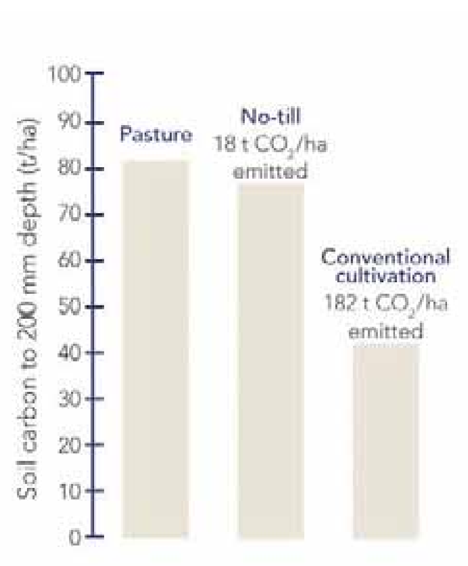
The **amount and form of nitrogen applied** to the soil (see scorecard, p. 89) can provide a further indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 9). The nitrification of urea and ammonium-based fertilisers, and particularly the denitrification of nitrates in the soil resulting from the excessive application of salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Fertiliser N applications stimulate emissions in the spring, while crop residues and their incorporation into the soil stimulate emissions in autumn and winter. The highest emissions occur following each fertiliser application, particularly when associated with major rainfall events. Seventy-five to eighty percent of the N_2O emitted can occur within 4 weeks of N application. While N_2O emissions can often account for up to 3 percent of the N applied as fertiliser in small-grain cereal crops and up to 8 percent in maize crops, compact, wet soils can increase N_2O emissions by denitrification 3–4-fold, resulting in a loss of up to 20 percent of fertiliser N, and also decreasing wheat yields by 25 percent. Yield reductions can be attributed in part to N deficiency by high denitrification activity and low mineralization. In addition, the excessive use of nitrogenous products can reduce the capacity of soils to take up and oxidise atmospheric CH_4, thereby reducing the ability of the soil to act as a CH_4 sink.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied to crops could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic and fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70%) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides micro-sites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root development, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70%, they can increase NH_3 emissions and potential NH_4^+-N leaching losses. The jury is also still out as to their long-term impact on soil biology, in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reductions in white clover. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

The **method of cultivation** (see scorecard, p. 89) can have a marked effect on the level of GHG emissions. Carbon dioxide emissions are significantly greater under conventional cultivation than other forms of ground preparation because of the greater loss of soil C (Figs 10 & 11). The high level of soil disturbance under conventional cultivation aerates the soil, increasing the mineralisation and oxidation of organic C to CO_2 by microbial respiration which subsequently volatilises into the atmosphere. If we assume that one tonne of organic C oxidises to 3.67 tonnes of CO_2, the loss of 31.6 t C/ha after 11 yrs of conventionally cultivated maize gives rise to the emission of approximately 116 t CO_2/ha (Fig. 10). The loss of 49.6 t C/ha after 35 yrs of continuous barley produces 182 t CO_2/ha. These figures do not, however, take into account the C added to the soil from the plant over the 11- and 35-year cropping period, C that would also have oxidised and potentially contributed to CO_2 emissions. However, as mentioned above, after CO_2 escapes from the

FIGURE 11 **Soil C loss and associated CO_2 emissions under no-till and conventional cultivation**



Soil C loss and associated CO_2 emissions under 20 yrs of double cropping using no-tillage and 35 yrs conventional cultivation.

soil, almost all of it is absorbed by the stomata on the crop leaves and is therefore recycled back into the soil. In addition to the major period of CO_2 emissions when the soil is tilled using conventional cultivation, a certain amount of CO_2 would be emitted after the harvest or senescence of one crop, and canopy closure of the next crop.

In comparison, the loss of soil organic C under no-tillage is significantly less than under conventional cultivation, producing as a result, less emissions of CO_2 (Fig. 11). Adopting carbon capture and storage (CCS) management practices including those cultivation practices that minimise C loss or even promoting C sequestration, is an effective means of reducing the emissions of CO_2 into the atmosphere.

Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by the Emissions Trading Schemes. If the GHG Emission Index is ≤ 22, certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of > 22 provides significant environmental benefits because less GHGs would be emitted into the atmosphere.

FIGURE 12 **Scorecard – visual indicators to assess the potential for greenhouse gas emissions**

Landowner:

Land use:

Site location:

GPS ref:

Sample depth:

Topsoil depth:

Soil type:

Soil classification:

Drainage class:

Date:

Textual group (upper 1 m): ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey ☐ Other

Visual indicators of GHG emissions	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below[1]) g. 2		x 2	
Soil porosity g. 6		x 3	
Number and colour of soil mottles g. 8		x 3	
Soil colour g. 10		x 2	
Crop yield g. 58		x 2	
Amount and form of N applied (Scoring protocol is given below[2])		x 1	
Method of cultivation (Scoring protocol is given below[3])		x 3	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 12
Moderate potential GHG emissions	12–22
Low potential for GHG emissions	> 22

1 **Textural group (Figure 2b, p. 3):**
VS = 2 for Sandy and Coarse loamy; **VS = 1.5** for Coarse silty; **VS = 1.0** for Fine loamy; **VS = 0.5** for Fine silty; **VS = 0** for Clayey.

2 **Amount and form of N applied:**
VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; **VS = 1** if 120–160 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; **VS = 0** if ≥ 200 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 **Method of cultivation:**
VS = 2 if using no-till practices; **VS = 1.5** if using strip tillage; **VS = 1** if using minimum tillage; **VS = 0.5** if using a mouldboard plough with limited secondary cultivation; **VS = 0** if using continuous conventional (mouldboard plough) cultivation with intensive secondary cultivation.

Soil management of maize crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, include 'pasture cropping' where annual crops are direct-drilled into perennial pastures, and no-tillage and minimum tillage practices that incorporate the establishment of temporary cover crops and crop residues on the surface. They provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage can also maintain soil life and biological activity (including earthworm numbers), and can increase micro-organism biodiversity above levels commonly found under conventional cultivation. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO_2) and enables the soil to operate as a sink for CO_2. Soil organic matter levels can build up as a result and create the potential to gain 'carbon credits', thereby providing an offset to greenhouse gas emissions. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

Where possible, put in place management strategies that don't require the use of herbicides. Avoid a monochemical herbicide strategy and manage the use of herbicides in association with crop rotations, including the use of livestock, to avoid the development of herbicide tolerance and residual effects. Ensure the soil has adequate levels of available Ca because herbicides are generally more effective when Ca levels in the plant are good. Also ensure that P levels aren't too high; the higher the P level, the harder it is to deal to snails and slugs. The inappropriate and over-use of various herbicides can significantly change nutrient availability and the efficient uptake of nutrients by binding up micronutrients (chelation immobilization), and through toxic effects on soil organisms important for nutrient turnover and supply.

Continuous conventional cultivation can impact negatively on the environment with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO_2), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades

PLATE 53 **A good maize crop**

Photo: Courtesy of of Kenneth G. Cassman

A good maize crop producing a grain yield in excess of 20 t/ha due in part to the adoption of good management practices that promote a good root system. Note the good potential rooting depth and root development to > 2m.
Compare with Plate 16, p. 23

soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. Conventional cultivation should be practiced on a rotational basis with 2 years of cropping followed by 5–7 years pasture.

The fundamental difference between continuous conventional cultivation and conservation tillage is their relative environmental and economic sustainability. The long-term affects of continuous conventional cultivation can be cumulatively negative whereas the long-term affects of conservation tillage can be cumulatively positive. This is provided that good residue management practices are applied and the herbicides used are 100% biodegradable and have no adverse effects on soil or human health.

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for maize*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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FIELD GUIDE

part 2

Maize

Visual indicators of environmental performance under cropping

A GUIDE

BioAgriNomics

UNIVERSITÀ DEGLI STUDI

FIELD GUIDE

VISUAL SOIL ASSESSMENT

Maize

Visual indicators of environmental performance under cropping

A GUIDE

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List of acronyms

AEC	Adenylate energy charge
Al	Aluminium
ASC	Anion storage capacity
ATP	Adenosine triphosphate
B	Boron
C	Carbon
Ca	Calcium
Ca^{2+}	Calcium cation
CEC	Cation exchange capacity
CH_4	Methane
CO_2	Carbon dioxide
qCO_2	Metabolic quotient
Co	Cobalt
Cu	Copper
Fe	Iron
FeS	Ferrous sulphide
Fe^{3+}	Ferric iron
Fe^{2+}	Ferrous iron
GHG	Greenhouse Gas
H_2S	Hydrogen sulphide
K	Potassium
K^+	Potassium cation
Mg	Magnesium
Mg^{2+}	Magnesium cation
Mn	Manganese
Mn^{3+}	Manganic ions
Mn^{2+}	Manganous ions
Mo	Molybdenum
N	Nitrogen
N_2	Nitrogen gas
NO_3^-	Nitrate
NO_3^--N	Nitrate-nitrogen
NO_2^-	Nitrite
N_2O	Nitrous oxide
Na	Sodium
Na^+	Sodium cation
NH_3	Ammonia
NH_4^+	Ammonium
O_2	Oxygen
P	Phosphorus
PO_4^{3-}	Phosphate
pH	Concentration of H^+ ions (Soil acidity/alkalinity)
RSG	Restricted spring growth
S	Sulphur
SO_4^{2-}-S	Sulphate-sulphur
SO_4^{2-}	Sulphate
SO_3^{2-}	Sulphide
VS	Visual score
VSA	Visual Soil Assessment
WFPS	Water-filled pore space
Zn	Zinc
ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER CROPPING

A GUIDE

Courtesy of Pioneer® brand products

1. Potential for nutrient loss into the groundwater and waterways

2. Carbon sequestration

3. Green house gas emissions

1. Visual indicators to assess the potential for nutrient loss into the groundwater and waterways

Assessment

1. To assess the susceptibility of soils under crops to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 71), the visual scores (VS) for Textural group, Soil colour, Soil smell, and Potential rooting depth from the Soil Scorecard, and the visual score (VS) for Root development from the Plant Scorecard. Also add a ranking score for the amount and solubility of fertiliser and nitrogenous products applied per annum (see scorecard). Multiply the VS by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Potential Nutrient Loss Index.

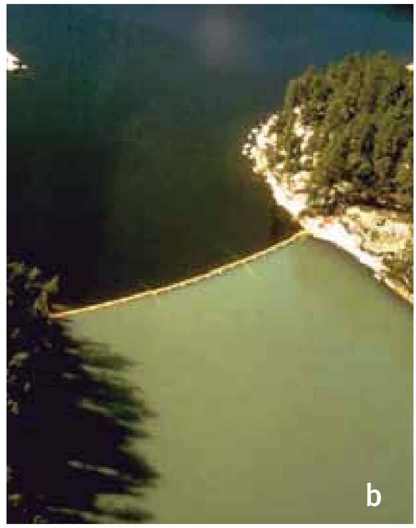
Importance

THE POTENTIAL FOR NUTRIENT LOSS into the groundwater and waterways is influenced by a number of factors, including rainfall and the ability of the soil to adsorb and hold nutrient cations and anions (known as the cation exchange capacity or CEC, and anion storage capacity or ASC). A rough positive correlation exists between the amount and kind of clay and humus in the soil and the CEC and ASC. The greater the amount of clay and humus present, the higher the CEC and therefore the more cations such as Ca^{2+} and Mg^{2+} can bond to clay particles and organic carbon, thus retaining a significant pool of nutrients in the soil that could otherwise be readily leached. Soils that contain high amounts of amorphous/non-crystalline clay minerals[1], have a high ASC and can therefore strongly adsorb anions such as phosphate (PO_4^{3-}) thereby making P less leachable.

Nutrient loss from the soil, including N, P, K, S, Ca, Mg, K, and Na, adversely affects soil/plant/animal and human health, and the productive and economic performance of a farm. Nutrient losses into the groundwater and waterways also have significant environmental effects, including accelerated greenhouse gas emissions, the build up of nitrate levels in the groundwater, and the eutrophication of waterways. The ratio of C, N, and P in aquatic microbial life is 40C:7N:1P and if the nutrients in the water differ from this, either N or P can control the overall level of algal growth. If the N:P is greater than 7:1, P is limiting growth. If the N:P is less than 7:1, then N will be the limiting factor. Given that most waterways have a N:P >7, it is P that is commonly most responsible for algal growth and the eutrophication of waterways (Plate 48b). Reducing the leaching of organic and inorganic forms of N and P will reduce nutrient losses, which in turn will reduce the nitrification of the groundwater and the eutrophication of waterways.

[1] Non-crystalline iron and aluminium hydrous oxides and amorphous alumino-silicate clay minerals such as ferrihydrite and allophone.

PLATE 48 **Nutrient loss into waterways**



a) A field with a moderate potential for nutrient loss into the groundwater and lake. While it has a coarse loamy textural group and moderately good structure with a moderately rapid permeability, it has moderately high carbon levels and CEC in the topsoil, good potential rooting depth, good root development, and received moderate amounts of water-soluble fertiliser and nitrogen.
b) Severe eutrophication of a lake with blue-green algae in the foreground due to phosphorus. The clear blue area received C and N; the green area received C + N + P from fertiliser. (Taken from D.W. Schindler)

The potential of a soil to lose nutrients into the groundwater and waterways can be roughly assessed from five of the soil and plant indicators used to assess soil quality and plant performance, as well as from the amount and form of fertiliser and nitrogenous products used, as described below.

Soil texture (p. 2) – Soil texture affects the flow rate (hydraulic conductivity) of water through the soil and the drainage status of the soil, both of which affect the leachability of nutrients. The hydraulic conductivity of a sandy soil is greater than that of a clayey soil and therefore the rate of leaching is faster through coarse textured soils. Clayey soils are also likely to be more poorly drained than sandy soils and therefore tend to be saturated for a greater length of time and have a shallower groundwater (high water table). As a result, nitrate-N (NO_3^--N) and nitrite (NO_2^-) are more likely to be reduced to nitrous oxide (N_2O) and nitrogen gas (N_2) through denitrification, reducing the concentration of nitrate in the soil and the amount that leaches into the groundwater and waterways.

In addition, sandy soils are low in colloidal clay and often deficient in humus, and as a result have a low CEC. Fine textured (clayey and fine silty) soils, on the other hand, contain more clay and generally more humus as well. Hence their CECs are higher and more able to adsorb and retain positively charged nutrients such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, NH_4^{+}, etc. Textural groups can therefore provide a useful indication of the potential of a soil to hold or leach nutrients.

Soils with a humic or peaty textural qualifier (e.g. *humic* silty clay, *peaty* silt loam) contain moderately high to high levels of organic carbon respectively, and are not only inherently rich in nutrients as a result, but are also able to adsorb a greater number of nutrients to their surface, releasing them slowly by the mineralisation activity of soil organisms. The nutrients are therefore less leachable and more likely to be taken up by the roots. Humic or peaty textural qualifiers can therefore provide an additional indication of the potential of a soil to hold or leach nutrients. Humic soils contain 10–17 percent total organic C (17–29 percent organic matter), and peaty soils contain 18–30 percent total organic C (30–50 percent organic matter).

Soil structure (p. 4) has a strong influence on the potential for nutrient loss in a soil. Soils with good structure and many conducting macropores have higher infiltration rates of water into the soil, and higher flow rates of water through the soil, compared with poorly structured soils. Nutrients are therefore able to be more rapidly leached through soils on flat land with better structure leaving less opportunity for plant uptake, denitrification, or immobilisation to remove nitrate and other nutrients from the soil solution. Organic N and P can also readily leach into the groundwater in well-structured soils through preferential flow.

Soils with poor structure are likely to be more poorly drained and waterlogged for longer periods, reducing the leaching of N by converting nitrate-N to nitrous oxide and nitrogen gas through denitrification.

The poorer the soil structure, the slower the infiltration of water into the soil, and the slower the flow rate of water through the soil. While the rate of leaching is reduced, runoff (overland flow) is increased. Run-off can therefore be a primary contributor to nutrient loss into waterways on poorly structured soils on undulating to rolling land. Organic N and P are also easily lost through runoff into the streams and lakes on poorly structured soils.

Potential rooting depth (p. 22) and the **Root development** (p. 46) – Crops with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with crops with a shallow, sparse root system. Soil nutrients are more likely to be sapped up and utilised and less likely to by-pass the root system, resulting in less leaching into the groundwater and waterways. The number and depth of roots can be readily determined by assessing the root development and the potential rooting depth.

The **amount and form of fertiliser and N applied** (see scorecard – p. 79) can significantly influence nutrient loss. Highly soluble fertilisers and granular nitrogenous products readily dissolve in water and can give rise to large losses of nutrients by surface runoff on heavy, compacted soils, and by leaching into the groundwater and connecting waterways on light, well-structured soils, particularly when applied in large amounts. High rates of fertiliser are also applied to crops in an attempt to overcome sparse root systems and maximise yield. The over-use of highly soluble granulated N products readily leaches cations (otherwise known as nitrate-induced cation leaching or cation stripping). When an anion such as nitrate is leached, equivalent amounts of cations will also be leached as counterions for NO_3^-. Calcium and to a lesser extent Mg^{2+} are the major counterions for NO_3^- leaching. Nitrate and H^+ ions are produced following the hydrolysis and subsequent nitrification of urea. The H^+ ions can also displace other cations on the soil exchange sites, resulting in a greater quantity of potentially leachable cations being present in the soil solution. Because Ca^{2+} is the dominant exchangeable cation in most soils, it is the predominant cation displaced and subsequently leached. It is partly for this reason that the application of urea and other salt-based nitrogenous fertilisers should always be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes. In contrast to urea and other highly soluble fertiliser products, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of high analysis, highly soluble forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can have a negative affect on soil life. The microbial biomass and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied could be markedly reduced, thereby reducing its loss. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic/fulvic acids). Adding a form of organic C to fertiliser and nitrogenous products, and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–65 percent) promotes the efficient plant uptake of N. The addition of stable inorganic forms of C such as biochar also provides micro-sites that attract soil microbes, increase the water-holding capacity by trapping moisture in its tiny pores, and help the soil to hold nutrients, thus reducing leaching. In addition, promoting the amount of humus, earthworms, potential rooting depth, root length and density, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^--N) from soluble nitrogenous products by 30–70 percent, they can also increase the potential for the leaching of NH_4^+-N. Moreover, the jury is still out as to their long-term impact on soil biology, both in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reduction in white clover. Because of these and other issues, including rate of biodegradation, persistence in the soil, and conflicting evidence on the effects and benefits of N-inhibitors on mitigating N losses into the groundwater, much more independent research needs to be carried out under conditions that represent typical cropping practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Any one of the above indicators provides an estimate of the susceptibility of the soil to lose nutrients into groundwater and waterways. Collectively, they provide a good overall assessment of a soil's potential for nutrient loss. If the Potential Nutrient Loss Index is ≤ 20, certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 20 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching into the environment. Crops are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth.

FIGURE 5 **Scorecard – visual indicators to assess the potential for nutrient loss**

Landowner:	**Land use:**
Site location:	**GPS ref:**
Sample depth:	**Topsoil depth:**
Soil type:	**Soil classification:**
Drainage class:	**Date:**

Textural group (upper 1 m): ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey ☐ Other

Visual indicators of nutrient loss		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below[1])	pg. 2		x 3	
Soil structure (Scoring protocol is given below[2])	pg. 4		x 2	
Potential rooting depth (mm)	pg. 22		x 3	
Root development	pg. 46		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below[3])			x 3	
NUTRIENT LOSS INDEX (sum of VS rankings)				

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 11
Moderate potential for nutrient loss	11–20
Low potential for nutrient loss	> 20

1 **Textural group** (Figure 2b, p. 3):
VS = 2 for Clayey; **VS = 1.5** for Fine silty; **VS = 1.0** for Fine loamy; **VS = 0.5** for Coarse silty; **VS = 0** for Coarse loamy & Sandy. If the soil has a humic or peaty textural qualifier (e.g. humic silty clay, peaty silt loam), add 0.5 or 1.0 rispectively to the VS score. Note VS scores cannot exceed a value of 2.

2 **Soil structure – Is the land most susceptible to a) leaching, or b) runoff?**
a) Land susceptible to leaching – Flat land with little or no runoff (overland flow)
VS = 2 for Poor soil structure; **VS = 1.5** for Moderately poor soil structure; **VS = 1.0** for Moderate soil structure; **VS = 0.5** for Moderately good soil structure; **VS = 0** for Good soil structure.
b) Land susceptible to runoff – Gently undulating to rolling land
VS = 2 for good soil structure; **VS = 1.5** for Moderately good soil structure; **VS = 1.0** for Moderate soil structure; **VS = 0.5** for Moderately poor soil structure; **VS = 0** for Poor soil structure

3 **Amount and form of fertiliser and N applied**
VS = 2 if using liquid foliar sprays or low water-soluble, salt-based fertilisers in low to moderate amounts. If using highly soluble, granular forms of N and fertiliser, < 15 kg P/ha/yr and/or ≤ 80 kg N/ha/yr are applied; **VS = 1.0** if using moderately water-soluble fertilisers in moderate amounts, or applying 25–35 kg P/ha/yr and/or 160–240 kg N/ha/yr, using highly soluble, salt-based and nitrogenous fertilisers; **VS = 0** if using highly water-soluble, salt-based and granular nitrogenous fertilisers in high amounts where > 45 kg P/ha/yr and/or > 320 kg N/ha/yr are applied.

2. Visual indicators to assess the potential for carbon sequestration

Assessment

1. Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 8, p. 79) the visual scores (VS) for Soil texture, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root development and Crop yield from the Plant Scorecard. Add also a ranking score for the clay mineralogy, the amount and form of fertiliser and nitrogen applied per annum, and for the method of cultivation (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the Soil Carbon Index. An increase in the Soil Carbon Index compared with previous assessments can indicate C sequestration.

Importance

THE AMOUNT OF C in a soil = C inputs – decomposition rates. A soil is carbon positive if the amount of C sequestered (i.e. added and held) is greater than the amount of C lost through decomposition, leaching and volatilization (Plate 49). A soil is carbon neutral if the total soil C is at steady state, i.e. C inputs equal outputs and the total C is neither increasing nor decreasing. A soil is carbon negative if the total soil C is decreasing, i.e. C inputs are less than the decomposition rates (Plate 50). Farmers can reduce their ecological and carbon footprint and 'grow' their soils by sequestering significant amounts of C through ensuring their farm management practices and soils are C positive. The sequestration of soil C improves soil physical, chemical and biological properties and processes, and reduces agriculture's contribution to greenhouse gas emissions, providing a cost- effective strategy to help mitigate climate change. In addition, C credits gained can help off-set green house gas emissions.

The dynamics of soil carbon and whether a farm is likely to be carbon positive, carbon neutral or carbon negative can be roughly estimated from the clay mineralogy, four indicators of soil quality, two indicators of plant performance, and from the method of cultivation and the amount and form of fertilisers and nitrogen used, as described below. Crops such as maize silage where most of the plant is removed are C negative.

Soil texture (p. 2) can provide a rough indication of the potential for C sequestration in the soil. The greater the clay content, the greater the surface area and surface charge, and therefore the greater the ability of organic C to bond to the soil as stable organo-clay complexes, which enables the amount of soil C to increase. In addition, clay particles are < 2 μm and allow soil C to be occluded in micropores small enough to physically protect it from microbial decomposition.

PLATE 49 **A carbon positive field**

Photo: Courtesy of Baker No-Tillage Ltd

A carbon positive field using no-till technology to sow directly into maize residue left on the surface. The field has good soil colour compared with the fenceline, good root development, potential rooting depth, and crop yields, moderate earthworm numbers, and 80 kg N/ha/yr are applied in a carbon-friendly form.

PLATE 50 **A carbon negative field**

A carbon negative field under continuous conventional cultivation. The field has moderately poor soil colour compared with the fenceline, poor earthworm numbers, moderate potential rooting depth, root development, and crop yields, and 200 kg N/ha/yr are applied in a non-carbon friendly form. Total organic C in the upper 200 mm of soil declined from 90.8 tonnes/ha under permanent pasture to 41.2 tonnes/ha after 35 yrs of continuous conventional cultivation (Figure 6, p. 77).

Clay mineralogy (see scorecard, p. 79) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Andosols) formed from volcanic ash and parent materials under high rainfall are dominated by Fe & Al hydroxides and alumino-silicate clay minerals (allophane, imogolite, ferrihydrite). These minerals are amorphous (poorly crystalline) with a very small particle-size and a high specific surface area and as a consequence are able to strongly bond to and adsorb organic C. adsorb organic C. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under 20 yrs continuous barley contain about 229 t C/ha in the top 1m, of which 159 t C/ha (69 percent) occurs in the upper 300 mm, and 70 t C/ha (31 percent) between 300 and 1000 mm. Compare this with non-allophanic soils below. The amount of C in the upper 300 mm of allophanic soils under cropping is only 4 t/ha less than under permanent pasture, illustrating its relative stability despite continuous, long-term conventional cultivation.

Soil colour compared with that under the fenceline (p. 10) can provide a good indication of the amount of organic matter and humus in the soil – by and large, the darker the colour, the greater the amount of organic matter and humus and therefore the higher the amount of C present. With the exception of poorly aerated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C (Fig. 10, p. 86).

Earthworms (p. 14) – Organic matter, humus and dead and living soil organisms, all major forms of carbon, provide the primary food source for soil life. The number of earthworms and soil organisms are therefore governed by the food supply, i.e. the amount of organic matter, humus, and dead and living soil organisms present. High numbers of earthworms and other soil organisms can only be supported by a large food supply, which indicates high amounts of C. High numbers of earthworms also ingest considerable plant material, building up soil C levels by converting it to more stable organic compounds bonded to clay particles. In addition, they increase the depth of topsoil by the deposition of worm casts and bioturbation.

Deep burrowing earthworms (such as the *Aporectodea longa*) can also relocate and deposit considerable amounts of plant residue, humus and other forms of carbon at depth. The number and activity of soil microbes at depth is much less than in the topsoil and so the carbon is more protected and able to build up because it is less likely to be mineralised. Deep burrowing earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil C.

Potential rooting depth (p. 22) and the **Root development** (p. 46) can also provide a good indication of the potential for C sequestration in the soil. Roots are comprised of approximately 41 percent carbon and as such can potentially add a significant amount of C to the soil by their cycle of growth and decomposition. Moreover, roots secrete large amounts of root exudates that are also high in C. Soils with a good root length and root density and a good potential rooting depth can therefore contribute substantial amounts of C to not only the topsoil but also to the subsoil. So, when assessing the amount of C actually sequestered by the soil, it is important to assess the amount of C in the potential rooting zone rather than in an arbitrary shallow depth such as the upper 300 mm of soil, as adopted by the Kyoto Protocol.

Orthic Gley Soils (Eutric Gleysols) with a moderate potential rooting depth of 580 mm contain about 128 tonnes C/ha after 23 yrs cereal and maize cropping: 85 t C/ha (67 percent) occur in the upper 300 mm, and 42 t C/ha (33 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good potential rooting depth of 1 m contain about 134 t C/ha after 22 yrs maize cropping, of which 64 t C/ha (48 percent) occur in the upper 300 mm, and 70 t C/ha (52 percent) occur between 300 and 1000 mm. The deeper seated C, while significant, is also potentially more stable than the shallower occurring C and needs to be taken into consideration in any carbon accounting and emissions trading scheme. Note the significantly lower C levels of these soils under conventional cultivation compared with pasture (Fig. 6, p. 77).

Crop yield (p. 58) can provide a further indication whether soil C is increasing, decreasing or at steady state. The greater the crop yield, the greater the root and shoot mass, and therefore the greater the input of C from the root system and the decomposition of the additional surface litter and surface residue. A 14-tonne/ha crop of maize for grain would produce an above-ground C input from the surface litter and residue of approximately 7 t C /ha, and a below-ground C input of 2 t/ha from the roots, a total of 9 t C/ha. An 11- tonne/ha crop of maize adds a total of approximately 7.1 t C/ha to the soil, or 21 percent less than the higher producing crop. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the crop has good root development and potential rooting depth, and the soil is allophanic with a good earthworm population, and doesn't receive high applications of soluble, salt-based nitrogenous products. The application of high rates of granular N to boost yield, promotes the vegetative growth of the shoots relative to the roots. The over-use of N also creates lazy plants, encouraging a shallow root system and therefore less C input. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil. In addition, the microbial decomposition of roots, plant litter and husks produces rapidly decomposable (labile), slowly decomposable (moderately stable), and recalcitrant (stable) forms of organic C including Alkyl-C, the latter two forms of which can accumulate in the soil. The input of C in the soil from maize for silage is considerably less than maize for grain because much of the above ground vegetative matter is removed at harvest. Maize silage can therefore have a C negative effect.

While C inputs are influenced in part by the factors listed above, both C inputs and C losses (the latter determined by the decomposition rate of organic C) are governed by the soil life, pH, soil moisture and temperature. Soil moisture and temperature are by and large constant over time, and would therefore promote a steady state where C losses equalled C inputs, provided the other factors influencing C inputs were also constant. However, increasing dry matter production by increasing crop growth, and developing those factors that promote C sequestration all work collectively to increase the input of C, thus allowing the amount of C in the soil to increase. Climate change would have a significant effect on soil moisture and soil and air temperature, and would therefore alter the dynamics of the amount of C added and lost. Carbon sequestration would increase in those areas that became wetter and warmer, and decrease in the drier, colder areas.

Amount and form of fertiliser and nitrogen applied to cropping soils (see scorecard, p. 79) can have a significant effect on soil carbon levels. Some forms of fertiliser are more biologically and carbon friendly than others. For example, serpentine super, dicalcium phosphate, lime products, dolomite, gypsum, humates, organic compost, compost teas, animal manures, and seaweed-based fertilisers, etc., are more biologically friendly and have a greater soil conditioning effect than many other products. These can be described as 'smart' fertilisers, i.e. they provide the nutrients required by the plant and in a form that promotes soil life. When used in conjunction with other additives, including carbohydrates, salt, calcium and key trace elements, and when combined with good soil and crop management, good crop yields and C levels can be sustained and increased over the long term. The form in which essential elements are applied can also have an effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and is the preferred form for improving crop quality, and if the seedlings or crop are sensitive to chlorine.

Similarly, while nitrogen promotes crop growth and therefore the input of C into the soil, certain forms of N are more effective than others at sequestering C. For example, more soil C is sequestered when using N applied in the form of foliar sprays, ammonium nitrate, and bio-friendly nitrogenous products that contain a form of organic carbon and carbohydrate such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N. The excessive use of soluble granular forms of N and high analysis nitrogenous fertilisers also cause the dissolution of soil C, including humus, by providing soil microbes (which have a narrow C:N ratio of 4:1–9:1) with an oversupply of N. This enables the microbes to meet their nutritional N requirements to continue mineralising organic forms of C that have a wide C:N ratio of 10:1–100:1. The oversupply of N stimulates bacteria to mineralise 2–3 times the amount of humus they would ordinarily mineralise. Moreover, the high use of granular forms of N such as urea, reduce the earthworm and microbial biomass, further reducing C levels in the soil.

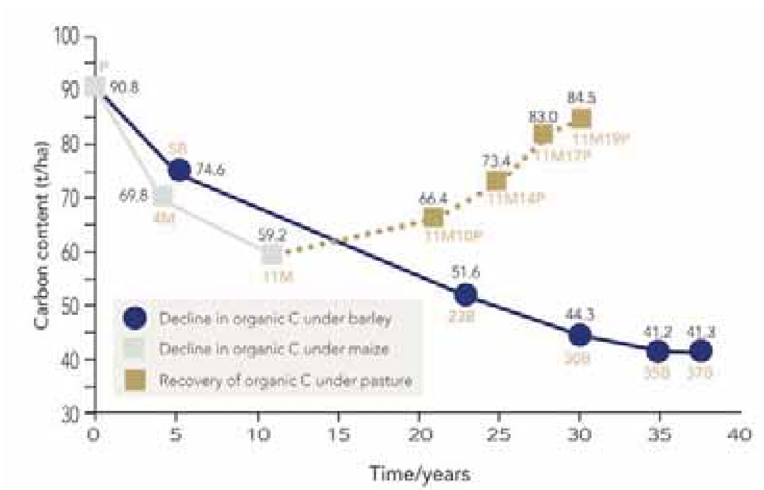
The plant converts CO_2 in the atmosphere into sugar (carbon) by photosynthesis in the leaves of the plant. The sugar dissolves as liquid glucose in the sap of the plant and is subsequently transferred to the soil through the roots to feed the soil microbes. The microbes in turn bring trace elements to the plant in exchange for the sugar. This process of C transfer from the plant to the soil, and the rate of photosynthesis, is disrupted by the over-use of high analysis, highly soluble forms of N and P. These include urea and anhydrous ammonia, and di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants, the rest is leached into the groundwater, lost as runoff into the waterways, and volatilised into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake. The amount of N applied could be markedly reduced, thereby reducing its effect on humus, if measures were taken to improve its utilisation. Such measures include the application of N as foliar sprays and in products that contain a form of organic C and carbohydrate (e.g., humates), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70 percent). The utilization of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root development, and crop yield.

The addition of stable, inorganic forms of C such as biochar to nitrogenous products and fertilisers can also increase C sequestration in the soil and provide micro-sites that attract soil microbes, increase the water holding capacity by trapping moisture in its tiny pores, and help the soil hold nutrients.

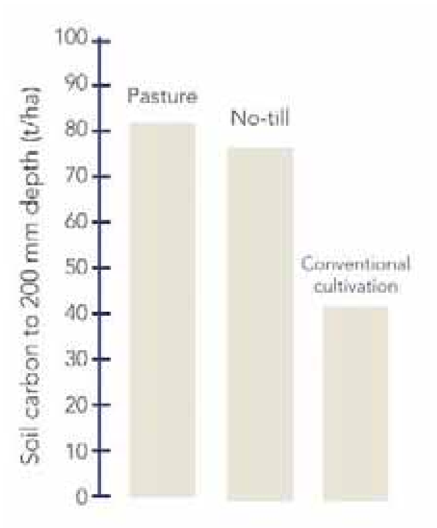
The **method of cultivation** (see scorecard, p. 79) can have a significant effect on soil C levels. Soil organic C can decline markedly under continuous conventional cultivation because the high level of soil disturbance aerates the soil, increasing the rate of mineralisation of soil organic C by microbial respiration and its oxidation to CO_2. The rate of C loss is particularly rapid in the first 4–5 years of cropping, followed by a slower rate of decline, eventually reaching an equilibrium where only the more stable and physically protected carbon remains in the soil (Fig. 6). Total soil C is seen in Fig. 6 to decline by 31.6 t/ha in the upper 200 mm of soil after 11 yrs continuous maize, and by 49.6 t/ha after 35 yrs continuous barley; an average loss of 2.9 and 1.7 t/ha/yr respectively. Note the initial slow rate of recovery of total C after 10 years of pasture following 11 yrs of maize. After 19 yrs of ryegrass/clover pasture, the total C had not recovered to pre-cropping pasture levels of 90.8 t/ha. The significant loss of C under both maize and barley, and the slow rate of C recovery under pasture are due in part to the poor management practices that prevailed. The slow rate of recovery of C under pasture was also due to the extremely compacted, poorly aerated state of the soil.

FIGURE 6 **Total C in the topsoil under pasture and continuous cropping**



Total C in the topsoil (0–200 mm) after 11 yrs and 37 yrs of continuous maize and barley respectively under conventional cultivation.
Note the rate of recovery of total C after 10, 14, 17 and 19 years of pasture following 11 yrs of maize.

FIGURE 7 **Total C in the topsoil under pasture, no-till and conventional cultivation**



Courtesy of Craig Ross

Total C in the topsoil under pasture, 20 yrs of double cropping (with a winter brassica and cereal crop) using no-till, and 35 yrs of conventional cultivation.

In comparison, the loss of soil C under no-tillage is significantly less than under conventional cultivation (Fig. 7). In some instances, C levels have increased in the upper 150 mm of soil under no-tillage compared with pasture. The greatest increases in soil C can occur at a depth of 300–600 mm under 'pasture cropping' practices where no herbicides or insecticides have been applied. The substantial loss of C under conventional cultivation and the slow rate of C recovery under pasture are due to the non-adoption of carbon capture and storage (CCS) management practices.

Any one of the above indicators provides an estimate of the ability of the soil to sequester C and therefore 'grow' the amount of C in the soil. Collectively, they provide a good overall assessment of whether a soil is likely to be C positive, neutral or negative. If the Soil Carbon Index is low or moderate (i.e. ≤ 32), certain management practices and specific types of fertiliser need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (> 32) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits.

FIGURE 8 Scorecard – visual indicators to assess the potential for carbon sequestration

Landowner: | **Land use:**
Site location: | **GPS ref:**
Sample depth: | **Topsoil depth:**
Soil type: | **Soil classification:**
Drainage class: | **Date:**

Textual group (upper 1 m): ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey ☐ Other

Visual indicators of soil carbon	Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below[1]) g. 2		x 2	
Clay mineralogy (Scoring protocol is given below[2])		x 2	
Soil colour g. 10		x 2	
Earthworms (Number =) (Av. size =) g. 14		x 3	
Potential rooting depth (mm) g. 22		x 3	
Root development g. 46		x 3	
Crop yield g. 58		x 3	
Amount and form of fertilizer and N applied (Scoring protocol is given below[3])		x 2	
Method of cultivation (Scoring protocol is given below[4])		x 3	
SOIL CARBON INDEX (sum of VS rankings)			

Soil Carbon Assessment	Soil Carbon Index
Potentially poor carbon levels	< 17
Potentially moderate carbon levels	17–32
Potentially good carbon levels	> 32

1 **Textural group: VS = 2** for Clayey; **VS = 1.5** for Fine loamy and Fine silty; **VS = 1.0** for Coarse silty; **VS = 0.5** for Coarse loamy; **VS = 0** for Sandy.

2 **Clay mineralogy: VS = 2** if the soil is dominated by Fe & Al hydroxides and amorphous aluminio-silica clay minerals with an anion storage capacity (ASC or P-retention) of > 85 percent; **VS = 1** if the soil has moderate levels of Fe & Al hydroxides and amorphous alumino-silica clay minerals with an ASC of 60–75 percent; **VS = 0** if the soil has little or no Fe & Al hydroxides and amorphous alumino-silica minerals; ASC is < 45 percent.

3 **Amount and form of fertiliser and N applied: VS = 2** if "smart" fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; **VS = 1** if 120–160 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based nitrogenous fertilisers; **VS = 0** if ≥ 200 kg N/ha/yr is applied as urea or in other non-carbon friendly forms of highly soluble, salt-based N fertilisers.

4 **Method of cultivation: VS = 2** if using 'pasture cropping' and no-till practices; **VS = 1.5** if using strip tillage; **VS = 1** if using minimum tillage; **VS = 0.5** if using a mouldboard plough with limited secondary cultivation; **VS = 0** if using continuous mouldboard ploughing with intensive secondary cultivation.

NB: A soil is carbon positive if there is a measurable increase in topsoil depth since the last assessment.

3. Visual indicators of potential greenhouse gas emissions

Assessment

1. Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 12, p. 89) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual score for Crop yield from the Plant Scorecard. Also add a ranking score for the method of cultivation used and the amount and form of N applied per annum (see scorecard). Multiply the visual scores by the weighting factor to get the VS ranking. Add up all the VS rankings to get the GHG Emission Index.

Importance

THE EARTH'S ATMOSPHERE is made up of 78 percent nitrogen and 21 percent oxygen with numerous trace gases, the most important of which are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). While occurring in only small amounts, each has an ability to absorb and trap heat, thus giving them the label of greenhouse gases (GHGs). Solar energy from the sun passes through the atmosphere, is absorbed by the Earth's surface, and warms it up. Greenhouse gases absorb some of the direct infra-red radiation and also some of the reflected heat energy from the earth's surface, keeping the earth's average temperature at about 15°C; without them the earth's average temperature would be around –18°C. However, the build-up of GHGs to elevated levels depletes stratospheric ozone and increases the temperature of the earth's surface and atmosphere, causing global warming.

Agriculture can provide a significant source of CH_4 and N_2O and is responsible for 15 percent of worldwide greenhouse gas emissions. CO_2 is emitted under arable cropping, however it is reabsorbed as photosynthate by the crop and is therefore greenhouse neutral. While high emission levels of GHGs are more to do with the way we farm, climate friendly and smart agricultural management can significantly reduce emissions.

GHG emissions from cropping result from a number of sources, including the soil, the burning of fossil fuels by farm machinery, and the production and application of nitrogenous fertilisers. The level of emissions varies according to a number of factors, including the condition of the soil, the method of cultivation, and the amount and form of fertiliser N applied, all of which are strongly influenced by farm management practices. Farmers can reduce their carbon footprint, i.e. their impact on the environment in terms of the amount of greenhouse gases produced, by reducing their GHG emissions. They can also do this by sequestering (i.e. adding and holding) significant amounts of C by the photosynthetic conversion of atmospheric CO_2 to soil C, and by promoting the soil as a CH_4 sink. The C credits gained can help off-set their GHG emissions.

PLATE 51 **Field with a low potential for greenhouse gas emission**

Field with a low potential to emit GHGs due to the soil being a well-drained, coarse loamy soil with good porosity under a no-tillage regime. In addition, good crop growth and yield remove a large amount of CO_2 from the atmosphere and CO_2 escaping from the soil by photosynthesis.

PLATE 52 **Field with a high potential for greenhouse gas emission**

Field with a high potential to emit GHGs due to the soil being an imperfectly to poorly drained, clayey soil with poor porosity under continuous conventional cultivation. In addition, poor crop growth and yield remove only small amounts of CO_2 from the atmosphere and CO_2 escaping from the soil by photosynthesis.

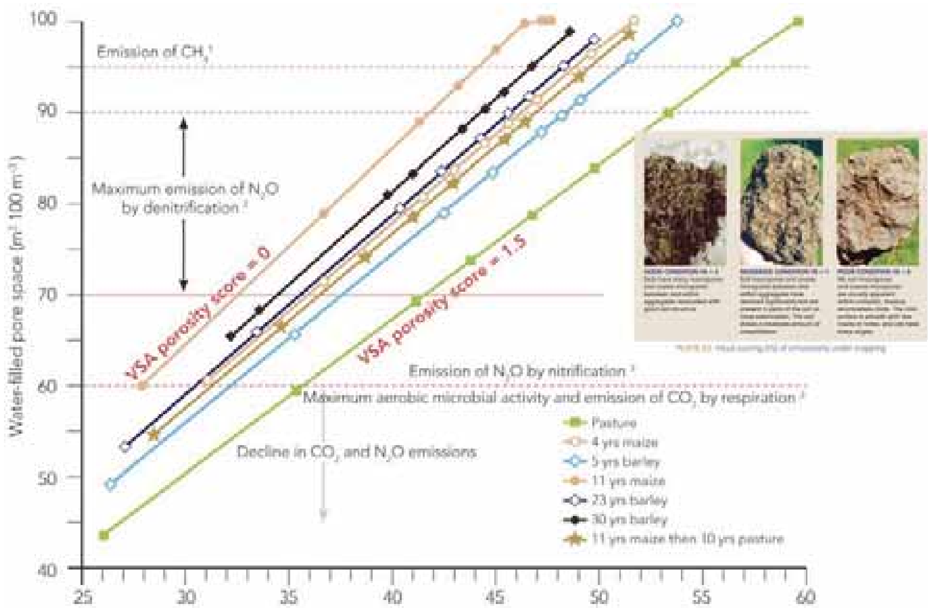
The potential of a site to emit GHGs can be roughly assessed from four indicators of soil quality, one indicator of plant performance, the amount and form of nitrogen applied, and the method of cultivation, as described below.

Soil textures (p. 2) influence the emission of GHGs partly because they affect the critical water-filled pore space (WFPS), which is a major 'driver' of GHG emissions, as discussed below. Finer textured soils such as clayey and fine silty textural groups reduce the critical WFPS, i.e. reduce the degree of saturation required to generate GHGs. They will therefore emit more GHGs throughout the year than coarser textured soils such as the coarse loamy and sandy groups, which increase the critical WFPS required to emit GHGs.

Soil porosity (p. 6), and in particular the amount of water present in the soil pores, otherwise referred to as the water-filled pore space (WFPS) or water-filled porosity (WFP), has a major bearing on the generation of GHGs. As soil pores become increasingly water-filled, CO_2 and N_2O, and finally CH_4 are emitted when the soil nears saturation. The emissions of both CO_2 by respiration and N_2O by nitrification increase linearly with increasing soil water content to a maximum of 60 percent WFPS, and then decrease. While the WFPS needs to be 60–65 percent for substantial emissions of N_2O to occur, the highest emissions occur by denitrification when the WFPS is between 70 and 90 percent (Fig. 9); emissions of N_2O are lowest when the WFPS is < 50 percent. Soils that have lost their macropores and coarse micropores, and have poor drainage between pores due to compaction or pugging, become water-filled quicker and for longer periods, and emit more GHGs than well-structured, well-aerated soils with good porosity and inter-pore drainage. The greater the number and size of soil pores and the better the drainage, the greater the amount and intensity of rainfall needed for pores to become sufficiently water-filled to produce GHGs. The number of days during the year when the soils are sufficiently wet to produce GHG emissions is therefore much greater for compacted, poorly drained soils than for well-aggregated, well-drained soils.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 9) requires a water content of approximately 42 percent (v/v) to ensure 70 percent of the soil pores are water filled and therefore able to generate significant emissions of N_2O. In contrast, a severely compacted soil after 11 yrs of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 9) requires a water content of only 33 percent (v/v) to reach the 70 percent WFPS required to increase N_2O emissions significantly. The severely compacted soil will therefore produce more GHGs than the well-structured soil because of the greater number of days during the year when the soil water content is at or above 70 percent WFPS. This is particularly significant in the case of N_2O because every 1 kg of N_2O emitted has the same Global Warming Potential (i.e. a heat-absorbing ability) as 310 kg of CO_2. While soils emit more GHGs in the wet winter months than in the drier seasons, emissions always spike after a heavy rainfall, regardless of the season. The intensity and duration of this spike can, however, be significantly reduced by ensuring the soil has good porosity and good drainage between pores. Promoting and maintaining the physical condition of the soil is

FIGURE 9 **Affect of water-filled pore space and water content on greenhouse gas emissions**



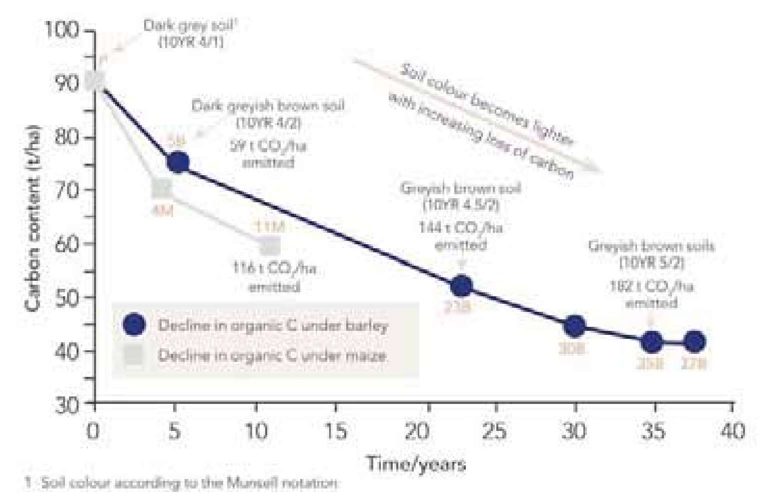
[1] After MacDonald *et al.* (1996); [2] After Dobbie *et al.* (1999); [3] After Linn and Doran (1984)

Water-filled pore space and water content at which GHGs are emitted in a Kairanga silty clay soil under pasture and at varying degrees of structural degradation under increasing periods of continuous cropping using conventional cultivation.

hence an effective means of reducing GHG emissions. The relationship between the WFPS and the visual assessment of the porosity of the soil, as shown in Fig. 9, can provide an immediate and very effective guide to the susceptibility of a soil to emit GHGs.

Soil mottles (p. 8) and **soil colour** (p. 10) are good indicators of drainage status and therefore of the susceptibility of the soil to emit GHGs. Many grey mottles and/or grey soil colours indicate the soil is poorly drained. Poorly drained soils emit greater amounts of GHGs than well-drained soils and take up less CH_4 from the atmosphere because fewer methanotrophic bacteria are present. Conversely, soils that do not have grey colours or a distinct greying of the soil and have no mottles, indicate well-aerated, well-drained conditions and are likely to emit comparatively small amounts of GHGs. Well-drained soils are also able to take up and oxidize CH_4 because of the greater number of methanotrophic bacteria present, significantly reducing CH_4 in the atmosphere. Such soils would therefore act as a more effective CH_4 sink. A lighter soil colour compared with soil under the fenceline can also indicate the loss of soil C and the emission of significant amounts of CO_2 into the atmosphere (Figure 10).

FIGURE 10 **Soil C loss and associated CO_2 emissions under continuous cropping**



Soil C loss, associated soil colour, and CO_2 emissions under continuous maize and barley cropping using conventional cultivation.

Crop yields (p. 58) can provide an indication of the potential to reduce GHG emissions. The greater the crop yield, the greater the amount of CO_2 removed from the atmosphere by photosynthesis and its conversion to soil C. This in turn helps off-set the CO_2 emitted by microbial respiration, the emission of GHGs from the consumption of the crop by stock, the burning of fossil fuels by farm machinery, and the application of nitrogenous fertilisers. As CO_2 escapes from the soil, most, if not or all, is absorbed by the stomata on the crop leaves, which have an insatiable appetite for CO_2. The greater the canopy cover (leaf area index) and the quicker the canopy closure, the greater the amount of CO_2 removed. Furthermore, if we assume that one kilogram of carbon in a maize crop removes 3.67 kg CO_2 from the atmosphere, a field growing 25 tonnes of maize silage/ha (or 10.3 t C/ha) will remove approximately 38 tonnes of atmospheric CO_2/ha. A field growing just 20 tonnes of maize silage/ha (or 8.2 t C/ha) will remove 30 tonnes of atmospheric CO_2/ha, 22 percent less than the higher producing field. While CO_2 is the least potent of the GHGs with a Global Warming Potential that is 21 and 310 times less than CH_4 and N_2O respectively, it is the most problematic of GHGs because of its sheer quantity. Promoting the photosynthetic conversion of CO_2 into sugars and oxygen, and subsequently into soil C, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Poor crop yield and the associated reduced crop cover would also reduce insulation from the sun, thereby increasing soil temperatures and reducing the uptake of available N and plant-available water, stimulating N_2O emissions by microbial nitrification and denitrification.

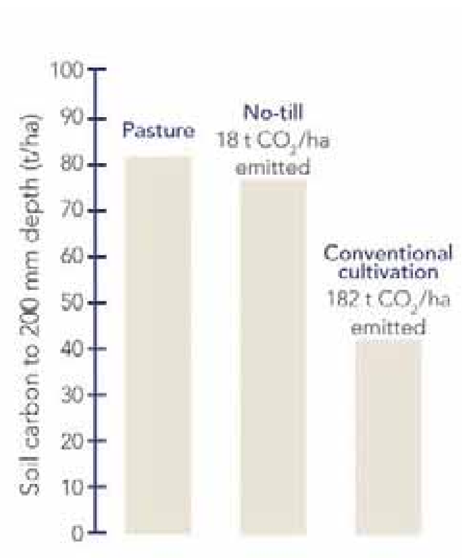
The **amount and form of nitrogen applied** to the soil (see scorecard, p. 89) can provide a further indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and denitrification, processes controlled by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil, as well as by soil temperature, rainfall, and the water-filled pore space (Fig. 9). The nitrification of urea and ammonium-based fertilisers, and particularly the denitrification of nitrates in the soil resulting from the excessive application of salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Fertiliser N applications stimulate emissions in the spring, while crop residues and their incorporation into the soil stimulate emissions in autumn and winter. The highest emissions occur following each fertiliser application, particularly when associated with major rainfall events. Seventy-five to eighty percent of the N_2O emitted can occur within 4 weeks of N application. While N_2O emissions can often account for up to 3 percent of the N applied as fertiliser in small-grain cereal crops and up to 8 percent in maize crops, compact, wet soils can increase N_2O emissions by denitrification 3–4-fold, resulting in a loss of up to 20 percent of fertiliser N, and also decreasing wheat yields by 25 percent. Yield reductions can be attributed in part to N deficiency by high denitrification activity and low mineralization. In addition, the excessive use of nitrogenous products can reduce the capacity of soils to take up and oxidise atmospheric CH_4, thereby reducing the ability of the soil to act as a CH_4 sink.

Only 40–50 percent of the N applied in conventional fertilisers may be utilized by plants. Apart from the losses from N_2O emissions, N is leached into the groundwater, lost as runoff into the waterways, and volatilised as N_2 gas into the atmosphere. Excess urea is often applied to crops to compensate for the inefficiency of N uptake and high losses. If measures were taken to improve its utilisation, the amount of N applied to crops could be markedly reduced, thereby reducing N_2O emissions. Such measures include the application of N as foliar sprays and in controlled release and bio-friendly forms, including products that contain organic C and carbohydrates (such as ammonium humate, humic and fulvic acids). Adding a form of organic C to nitrogenous products and ensuring that Ca levels in the soil are good (with a Ca base saturation of 65–70%) promote the efficient plant uptake of N. The addition of stable, inorganic forms of C such as biochar also provides micro-sites that attract soil microbes and help to hold nutrients, thus reducing emissions into the atmosphere. Emissions by volatilisation of N-based products can be further reduced by applying them before light rain or irrigation and onto moist rather than dry soil. In addition, promoting the amount of humus, potential rooting depth, root development, and crop growth improves the utilisation of N.

While the use of N-inhibitors can reduce N_2O emissions from urine patches and soluble nitrogenous products by 30–70%, they can increase NH_3 emissions and potential NH_4^+-N leaching losses. The jury is also still out as to their long-term impact on soil biology, in terms of microbial biomass, diversity and activity. The N-inhibitor DCD (Dicyandiamide), for example, interferes with the ability of methanotrophic bacteria in the soil to reduce CH_4 in the atmosphere. Nitrogen inhibitors also break down in the warmer weather and are therefore only effective in the colder winter months when soluble forms of N shouldn't be applied anyway. This is particularly so when winters are characterised by higher rainfall with a higher rate of leaching and lower soil temperatures, giving limited grass growth despite the application of N. Nitrogen inhibitors can further produce phytotoxic effects and yield reductions in white clover. Because of these and other issues, including the rate of biodegradation, persistence in the soil, and conflicting evidence as to the effects and benefits of N-inhibitors on mitigating N_2O emissions and N leaching into the groundwater, much more independent research needs to be carried out under conditions that are representative of typical farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

The **method of cultivation** (see scorecard, p. 89) can have a marked effect on the level of GHG emissions. Carbon dioxide emissions are significantly greater under conventional cultivation than other forms of ground preparation because of the greater loss of soil C (Figs 10 & 11). The high level of soil disturbance under conventional cultivation aerates the soil, increasing the mineralisation and oxidation of organic C to CO_2 by microbial respiration which subsequently volatilises into the atmosphere. If we assume that one tonne of organic C oxidises to 3.67 tonnes of CO_2, the loss of 31.6 t C/ha after 11 yrs of conventionally cultivated maize gives rise to the emission of approximately 116 t CO_2/ha (Fig. 10). The loss of 49.6 t C/ha after 35 yrs of continuous barley produces 182 t CO_2/ha. These figures do not, however, take into account the C added to the soil from the plant over the 11- and 35-year cropping period, C that would also have oxidised and potentially contributed to CO_2 emissions. However, as mentioned above, after CO_2 escapes from the

FIGURE 11 **Soil C loss and associated CO_2 emissions under no-till and conventional cultivation**



Soil C loss and associated CO_2 emissions under 20 yrs of double cropping using no-tillage and 35 yrs conventional cultivation.

soil, almost all of it is absorbed by the stomata on the crop leaves and is therefore recycled back into the soil. In addition to the major period of CO_2 emissions when the soil is tilled using conventional cultivation, a certain amount of CO_2 would be emitted after the harvest or senescence of one crop, and canopy closure of the next crop.

In comparison, the loss of soil organic C under no-tillage is significantly less than under conventional cultivation, producing as a result, less emissions of CO_2 (Fig. 11). Adopting carbon capture and storage (CCS) management practices including those cultivation practices that minimise C loss or even promoting C sequestration, is an effective means of reducing the emissions of CO_2 into the atmosphere.

Any one of the above indicators provides an estimate of the potential for the emission of GHGs. Collectively, they provide a good overall assessment of the susceptibility of a field (or farm) to emit GHGs and whether the emission levels are likely to be under or over the limit or 'cap' set by the Emissions Trading Schemes. If the GHG Emission Index is ≤ 22, certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of > 22 provides significant environmental benefits because less GHGs would be emitted into the atmosphere.

FIGURE 12 Scorecard – visual indicators to assess the potential for greenhouse gas emissions

Landowner:

Land use:

Site location:

GPS ref:

Sample depth:

Topsoil depth:

Soil type:

Soil classification:

Drainage class:

Date:

Textual group (upper 1 m): ☐ Sandy ☐ Coarse loamy ☐ Fine loamy ☐ Coarse silty ☐ Fine silty ☐ Clayey ☐ Other

Visual indicators of GHG emissions		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Textural group (Scoring protocol is given below[1])	g. 2		x 2	
Soil porosity	g. 6		x 3	
Number and colour of soil mottles	g. 8		x 3	
Soil colour	g. 10		x 2	
Crop yield	g. 58		x 2	
Amount and form of N applied (Scoring protocol is given below[2])			x 1	
Method of cultivation (Scoring protocol is given below[3])			x 3	
GHG EMISSION INDEX (sum of VS rankings)				

GHG Emission Assessment	GHG Emission Index
High potential for GHG emissions	< 12
Moderate potential GHG emissions	12–22
Low potential for GHG emissions	> 22

1 **Textural group (Figure 2b, p. 3):**
VS = 2 for Sandy and Coarse loamy; **VS = 1.5** for Coarse silty; **VS = 1.0** for Fine loamy; **VS = 0.5** for Fine silty; **VS = 0** for Clayey.

2 **Amount and form of N applied:**
VS = 2 if N is applied as a foliar spray or in controlled release and bio-friendly forms of fertiliser in low amounts; or ≤ 80 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; **VS = 1** if 120–160 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; **VS = 0** if ≥ 200 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

3 **Method of cultivation:**
VS = 2 if using no-till practices; **VS = 1.5** if using strip tillage; **VS = 1** if using minimum tillage; **VS = 0.5** if using a mouldboard plough with limited secondary cultivation; **VS = 0** if using continuous conventional (mouldboard plough) cultivation with intensive secondary cultivation.

Soil management of maize crops

Good soil management practices are needed to maintain optimal growth conditions for producing high crop yields, especially during the crucial periods of plant development. To achieve this, management practices need to maintain soil conditions that are good for plant growth, particularly aeration, temperature, nutrient and water supply. The soil needs to have a soil structure that promotes an effective root system that can maximise water and nutrient utilisation. Good soil structure also promotes infiltration and movement of water into and through the soil, minimising surface ponding, runoff and soil erosion.

Conservation tillage practices, include 'pasture cropping' where annual crops are direct-drilled into perennial pastures, and no-tillage and minimum tillage practices that incorporate the establishment of temporary cover crops and crop residues on the surface. They provide soil management systems that conserve the environment, minimise the risk of soil degradation, enhance the resilience and quality of the soil, and reduce production costs. Conservation tillage protects the soil surface reducing water runoff and soil erosion. It improves soil physical characteristics, reduces wheel traffic which lessens wheel traffic compaction, and does not create tillage pans or plough pans. It improves soil trafficability and provides opportunities to optimise sowing time, being less dependent on climatic conditions in spring and autumn. Conservation tillage can also maintain soil life and biological activity (including earthworm numbers), and can increase micro-organism biodiversity above levels commonly found under conventional cultivation. It retains a greater proportion of soil carbon sequestered from atmospheric carbon dioxide (CO_2) and enables the soil to operate as a sink for CO_2. Soil organic matter levels can build up as a result and create the potential to gain 'carbon credits', thereby providing an offset to greenhouse gas emissions. Conservation tillage also uses smaller amounts of fossil fuels, generates lower greenhouse gas emissions and has a smaller ecological footprint on a region, thereby raising marketplace acceptance of produce.

Where possible, put in place management strategies that don't require the use of herbicides. Avoid a monochemical herbicide strategy and manage the use of herbicides in association with crop rotations, including the use of livestock, to avoid the development of herbicide tolerance and residual effects. Ensure the soil has adequate levels of available Ca because herbicides are generally more effective when Ca levels in the plant are good. Also ensure that P levels aren't too high; the higher the P level, the harder it is to deal to snails and slugs. The inappropriate and over-use of various herbicides can significantly change nutrient availability and the efficient uptake of nutrients by binding up micronutrients (chelation immobilization), and through toxic effects on soil organisms important for nutrient turnover and supply.

Continuous conventional cultivation can impact negatively on the environment with a greater food eco-footprint on a region and a country. It reduces the organic matter content of the soil by microbial oxidation, increases green house gas emissions (including the release of 5-times more CO_2), uses more fossil fuels (i.e., 6-times more consumption of fuel), degrades

PLATE 53 **A good maize crop**

Photo: Courtesy of of Kenneth G. Cassman

A good maize crop producing a grain yield in excess of 20 t/ha due in part to the adoption of good management practices that promote a good root system. Note the good potential rooting depth and root development to > 2m.
Compare with Plate 16, p. 23

soil structure, increases soil erosion, and adversely alters microflora and microfauna by reducing both the number of species and their biomass. Conventional cultivation should be practiced on a rotational basis with 2 years of cropping followed by 5–7 years pasture.

The fundamental difference between continuous conventional cultivation and conservation tillage is their relative environmental and economic sustainability. The long-term affects of continuous conventional cultivation can be cumulatively negative whereas the long-term affects of conservation tillage can be cumulatively positive. This is provided that good residue management practices are applied and the herbicides used are 100% biodegradable and have no adverse effects on soil or human health.

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for maize*. FAO, Rome, Italy.

The present publication on **Visual Soil Assessment** is a practical guide to carry out a quantitative soil analysis with reproduceable results using only very simple tools. Besides soil parameters, also crop parameters for assessing soil conditions are presented for some selected crops. The **Visual Soil Assessment** manuals consist of a series of separate booklets for specific crop groups, collected in a binder. The publication addresses scientists as well as field technicians and even farmers who want to analyse their soil condition and observe changes over time.

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