VISUAL SOIL ASSESSMENT

FIELD GUIDE

part 2

Pastures

Visual indicators of environmental performance under pastoral grazing

A GUIDE

BioAgriNomics

UNIVERSITÀ DEGLI STUDI DI TERAMO

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Visual indicators of environmental performance under pastoral grazing

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
Cl	Chlorine
CO_2	Carbon dioxide
qCO_2	Metabolic quotient
Co	Cobalt
CT	Condensed tannins
Cu	Copper
DM	Dry matter
Fe	Iron
FeS	Ferrous sulphide
Fe^{3+}	Ferric iron
Fe^{2+}	Ferrous iron
GHG	Greenhouse Gas
H_2	Hydrogen gas
H_2S	Hydrogen sulphide
I	Iodine
K	Potassium
K^+	Potassium cation
KCl	Potassium chloride
LHb	Leghaemoglobin
Mg	Magnesium
Mg^{2+}	Magnesium cation
$MgCl_2$	Magnesium chloride
MgO	Magnesium oxide
Mn	Manganese
Mn^{3+}	Manganic
Mn^{2+}	Manganous
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_4^+	Ammonium
NH_3	Ammonia
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
Se	Selenium
VS	Visual score
VSA	Visual Soil Assessment
WFP	Water-filled porosity
Zn	Zinc
ZnS	Zinc sulphide

VISUAL INDICATORS OF ENVIRONMENTAL PERFORMANCE UNDER PASTORAL GRAZING

A GUIDE

1. Nutrient loss into the groundwater and waterways

2. Carbon sequestration

3. Greenhouse gas emissions

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

Assessment

❶ To assess the susceptibility of soils under pasture to lose nutrients into the groundwater and waterways, transpose to the Nutrient Loss Scorecard (Fig. 5, p. 79), the visual scores (VS) for the Textural group, Soil structure and the Potential rooting depth from the Soil Scorecard, and the visual scores (VS) for Root length and root density, Pasture quality, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Also add a ranking score for stocking rate and the amount and form 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 >7:1, P is limiting growth. If the N:P <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.

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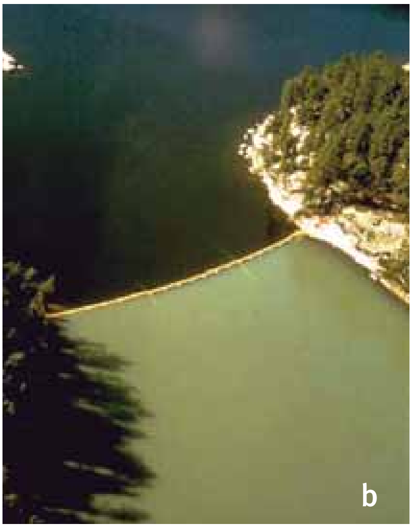
[1] Non-crystalline iron and aluminium hydrous oxides and non-crystalline alumino-silicate clays such as ferrihydrite and allophone.

PLATE 48 **Nutrient loss into waterways**



a) Paddock with a moderate potential for nutrient loss into the groundwater and lake. While the soil has a sandy textural group and good soil structure with a rapid permeability, it has a good potential rooting depth, moderately good root length and root density, moderately high carbon levels and CEC in the topsoil, and receives moderate amounts of low water-soluble fertiliser. The paddock has a moderate pasture quality with a moderately low stocking rate.

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 estimated from seven 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 in solution can also 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 length and root density** (p. 60) – Pastures with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for nutrients compared with pastures 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 length and root density and the potential rooting depth.

Pasture quality (p. 34) can provide a good indication of the potential for nutrient loss into the groundwater and waterways. Pastures rich in crude protein and nitrate-N with low sugar content are difficult for the micro-organisms in the rumen of the animal to break down by fermentation because of the lack of energy (sugars) in the pasture. As a consequence, livestock are only able to convert about 20 percent of the protein in the herbage into milk, meat and fibre. Furthermore, because of the low sugar levels, the rumen microbes do not have the energy required to utilize the excess N in the feed, converting 80 percent of it into ammonia as a consequence. As a result, the concentration of N in urine patches is markedly increased to 1 000–1 600 kg N/ha, increasing the amount of N lost by surface runoff and leaching into the groundwater and waterways. Leaching from urine patches accounts for about 55 percent of the total N leached from pastures. The amount of N lost can be significantly reduced by simply reducing the concentration of N in the urine by ensuring stock graze sugar-rich, nutrient-dense high quality pasture containing mature proteins, soluble non-structural carbohydrates, cobalt and condensed tannins.

Pasture colour and growth relative to urine patches (p. 52) can also provide a good indication of the potential for nutrient loss versus the retention and utilisation of nutrients in the soil (Plate 49). The greater the colour/growth contrast, the greater the loss potential. Poor growth and yellow pasture relative to urine patches often indicate the nitrogen and/or sulphur cycle has broken down. This is because the amount of humus and the number and activity of soil organisms responsible for nutrient retention, turnover and supply, have been degraded by, for example, the frequent and excessive application of artificial N and certain types of fertilisers, herbicides and pesticides. Without the humus and microbial population, subsequent applications of nutrients, particularly in the form of highly soluble fertilisers and N, will be more readily leached through the soil profile. The presence of

PLATE 49 **High potential for nutrient loss**

Paddock with a high potential for nutrient loss into the groundwater and waterways due partly to poor pasture quality and associated high concentration of N in the urine as indicated by the tall, dark green grass (nitrogen hills) in the urine patches compared with between urine patches.

tall, dark green grass in the urine patches compared with yellow, poor pasture growth areas between urine patches also indicates a high concentration of N in the urine and its subsequent potential for loss by leaching. In addition, organic acids released from animal manure, and the high pH of liquid manure and sewage sludge, enhance the mobilisation of phosphorus, increasing the amount of P that is leached.

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. The over-use of highly soluble granulated N products also 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 in urine patches. Nitrate and H^+ ions are produced in the urine patch 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 be accompanied by an active, on-going liming programme, including the incorporation of lime into fertiliser mixes.

The frequent addition of soluble nitrogenous products to boost dry matter production also increases the concentration of N in the herbage and subsequently, the concentration of N in the urine. Moreover, the extra amount of nitrate-rich pasture grown by applying N is consumed by the animal, producing a greater amount of urine. As a consequence, the production of additional amounts of N-rich urine increases the amount of N leached into the groundwater and waterways. In contrast, the application of 'smart' fertiliser products that help generate sugar-rich, nutrient-dense, high-quality pastures with a high metabolisable energy and digestibility, result in the animal producing lower concentrations of N in the urine. The energy demand of the animal eating higher quality pasture is also met by it consuming less, thereby producing less urine. In addition, the concentration of N in the urine is reduced by ensuring the animal intake of Co in the herbage is adequate to enable the bacteria in the rumen to produce vitamin B_{12} necessary to promote efficient digestion through good rumen function. To this end, Co levels in the pasture should be of the order of 0.1–0.15 mg/kg. The production of less urine with a lower concentration of N significantly reduces the input of N into the groundwater and waterways. Additionally, fertilisers with a low water solubility release nutrients slowly increasing their chance of being utilised by plant roots.

The over-use of soluble, salt-based forms of N and P including urea, anhydrous ammonia, di-ammonium phosphate (DAP), mono-ammonium phosphate (MAP), and superphosphate can strongly inhibit soil life. Soil microbes and earthworms can lock up (immobilise) significant amounts of nutrients, making them less leachable and therefore more available to the plant. Nutrient loss can therefore be reduced by applying fertilisers in a way that promotes soil life.

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 pastures 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 carbohydrates and organic C (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 60–70 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 pasture growth improves the utilisation of N.

While the use of N-inhibitors can reduce the leaching of nitrate-nitrogen (NO_3^--N) from urine patches and 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. It can further produce phytotoxic effects and yield reductions in white clover and clover N_2 fixation. 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. 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 farming practices. In addition, N-inhibitors are a high-cost option when there are a host of least-cost mitigation options available.

Stocking rate (see scorecard – p. 79) can significantly influence nutrient loss into the groundwater and waterways. Animal urine contains a lot of nitrogen and is the principal source of leached N in managed grazing systems (Plate 56, p. 98). The amount of urine produced is roughly proportional to the animal liveweight. A 500-kg dairy cow produces 13–27 litres of urine/day, approximately seven times the amount of a 70-kg ewe, which produces 1.8–3.6 litres of urine/day (Table 10). While urine patches can contain 1 000–

TABLE 10 **Average liveweight and the amount of urine produced for different stock classes**

Stock class	Average live weight (kg)	Stock unit equivalent [1]	Volume of urine per day (litres)	Volume of urine per year (litres)
Friesian cow	500–550	6.3	13–27	4 740–9 850
Jersey cow	400–450	5.3		
Beef cow	500–600	6.3		
Heffer	250–350	3.4		
Deer	120	2.1		
Goat	60			
Ewe	60–75	1.2	1.8–3.6	650–1 310
Hogget	50	1		
Lamb	35–40	0.7		

[1] Cornforth and Sinclair (1984).

1 600 kg N/ha, N leaching losses from dairy/beef and sheep farms commonly range from 15 to 115 and 10 to 66 kg N ha/yr respectively. The actual amount of N in urine strongly depends on the amount and form of soluble, salt-based nitrogenous fertiliser applied, the amount, quality and type of feed consumed, and the efficiency of rumen function. A high stocking rate on crude protein/nitrate-rich pasture receiving high amounts of soluble salt-based fertiliser N will significantly increase the amount of leached N compared with low stocking rates. All things being equal, 4 cows/ha will add roughly twice as much urinary N as 2 cows/ha.

Animal liveweight per hectare instead of stock units is used to define stocking rates because of the difficulty of accurately reporting stock units for different classes of livestock, and at different times of the year in terms of their size, feed (energy) requirements, animal performance and farming systems. The average liveweight per animal for different stock classes is given in Table 10 and can be quickly used to calculate stocking rate (and feed-use efficiency), regardless of the class of livestock.

Any one of the above indicators provides an estimate of the susceptibility of a 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 ≤ 28, certain management practices and types of fertiliser need to be applied to minimise the loss of nutrients. A Potential Nutrient Loss Index of > 28 provides significant environmental benefits where nutrients are more likely to be taken up by the plant, so reducing losses by leaching and surface runoff into the environment. Pastures are also less reliant on frequent and/or high application rates of fertiliser and nitrogen to generate growth. Farmer involvement is the key to reducing nutrient loss into the groundwater and waterways. The Nutrient Loss Scorecard provides farmers with a simple, quick tool to help them mitigate nutrients emissions into the environment.

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

Landowner: **Land use:** **Site:** **Date:**

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

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 length & root density	pg. 60		x 3	
Pasture quality	pg. 34		x 3	
Pasture colour & growth relative to urine patches	pg. 52		x 2	
Amount and form of fertilizer and N applied (Scoring protocol is given below[3])			x 3	
Stocking rate (Scoring protocol is given below[4])	pg. 77		x 2	
NUTRIENT LOSS INDEX (sum of VS rankings)				

Nutrient Loss Assessment	Nutrient Loss Index
High potential for nutrient loss	< 15
Moderate potential for nutrient loss	15–28
Low potential for nutrient loss	> 28

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 respectively 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 and hilly 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, conditioner, 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 ≤ 30 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 60–90 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 > 120 kg N/ha/yr are applied.

4 **Stocking rate – kg liveweight (Lwt) per ha**
VS = 2 if the Lwt is ≤ 1 000 kg (≤ 2 cows*)/ha; **VS = 1.5** if the Lwt is 1 250 kg (2.5 cows)/ha; **VS = 1** if the Lwt is 1 500 kg (3 cows)/ha; **VS = 0.5** if the Lwt is 1 750 kg (3.5 cows)/ha; **VS = 0** if the Lwt is ≥ 2 000 kg (≥ 4 cows)/ha. [* assuming a cow of 500 kg liveweight]

2. Visual indicators to assess the potential for carbon sequestration

Assessment

❶ Assess the Soil Carbon Index of a site by transposing onto the Carbon Scorecard (Fig. 7, p. 89) the visual scores (VS) for the Textural group, Soil colour, Earthworms, and Potential rooting depth from the Soil Scorecard, and the visual scores for Root length and root density, Pasture growth, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Add also a ranking score for the clay mineralogy and the amount and form of fertiliser and nitrogen 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 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 – C losses. Carbon inputs and losses are in equilibrium with soil temperature, moisture, mineralogy, drainage status, decomposition rates, leaching, volatilisation, farming systems, and soil and pasture management. With the exception of the last three, most of these governing factors remain fairly constant, providing a potential steady state in the carbon-carrying capacity of the soil. The equilibrium can, however, swing towards increasing soil C by increasing the input of relatively stable forms of carbon through adopting appropriate farm management practices. 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 (by oxidation and mineralisation), leaching and volatilization. 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 C losses. 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 CO_2 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, three indicators of plant performance, and from the amount and form of fertiliser and nitrogen applied, as described below.

PLATE 50 **Carbon positive soil**

A carbon positive soil with good soil colour compared with the fenceline, good potential rooting depth, pasture growth, pasture colour and growth compared with urine patches, moderately good earthworm numbers, root length and root density, and carbon-friendly forms of nitrogen applied annually in low amounts.

PLATE 51 **Carbon neutral soil**

A carbon neutral soil with moderate soil colour compared with the fenceline, moderate earthworm numbers, potential rooting depth, pasture growth, pasture colour and growth compared with urine patches, moderately poor root length and root density, and moderate amounts of granular nitrogenous products applied annually.

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 soil 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.

Clay mineralogy (see scorecard, p. 89) can have a significant influence on the soil's ability to sequester C. Allophanic Soils (Mollic 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. This enables these soils to sequester soil C more readily than most other soils. Allophanic soils with a good potential rooting depth under pasture contain about 235 t C/ha in the top 1 m, of which 163 t C/ha (69 percent) occur in the upper 300 mm, and 72 t C/ha (31 percent) between 300 and 1000 mm. Compare this with non-allophanic soils below.

Soils with a high proportion of amorphous (poorly crystalline) alumino-silicate clay minerals have a high anion storage capacity (ASC) while soils dominated by crystalline alumino-silicate clays have a low ASC. The ASC can therefore provide a useful indication of the proportion and general type of clay minerals present and can be used to broadly describe the clay mineralogy of the soil. The ASC is also commonly reported on most soil tests, and so farmers will have the information required to score this indicator, as defined in the scoring protocol on p. 89.

Soil colour compared with that under the fenceline (p. 10) can provide a rough 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 (Fig. 6, p. 88). With the exception of poorly aerated and saturated soils, a paling in soil colour can indicate a decline in organic matter and humus and therefore lower amounts of soil C.

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. Earthworms can therefore significantly increase carbon levels at depth and hence the sequestration of soil carbon. Soils are also less well aerated and have fewer microbes at depth and so organic carbon is more protected and able to build up because it is less likely to be oxidised and mineralised.

Potential rooting depth (p. 22) and the **Root length and root density** (p. 60) 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 160 tonnes C/ha, of which 117 t C/ha (73 percent) occur in the upper 300 mm, and 43 t C/ha (27 percent) occur between 300 and 580 mm. Fluvial Recent Soils (Eutric Fluvisols) with a good rooting depth contain about 173 t C/ha in the top 1 m, of which 103 t C/ha (60 percent) occur in the upper 300 mm, and 70 t C/ha (40 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.

Pasture growth (p. 50) provides a further indication that soil C is increasing, decreasing or at steady state. The greater the dry matter production, the greater the root and shoot mass, and therefore the greater the C input from the root system and the decomposition of the additional surface litter and animal dung. A farm growing 18 tonnes of dry matter (DM)/ha/yr with a shoot:root ratio of 1:1 adds similar amounts of plant material to the soil, of which 41 percent or 7.4 t/ha/yr is carbon. Approximately 6.2 t C/ha/yr is added to the soil from the roots and 1.2 t C/ha/yr from plant litter, assuming 84 percent pasture utilisation. A further 4.3 t C/ha/yr is added from animal excreta, making a total input of 11.7 t C/ha/yr. Of this, approximately 0.43 t C/ha/yr is incorporated as soil C. A farm growing just 15 t DM/ha/yr adds a total input of 9.8 t C/ha/yr, of which approximately 0.36 t C/ha/yr is incorporated as soil C, 16 percent less than the higher producing farm. While much of this is mineralised, a small amount can be sequestered annually, building up over time, particularly if the pasture is not overstocked, has good residual levels, root-length density, and potential rooting depth, and the soil is allophanic with good soil life and doesn't receive high applications of salt-based nitrogenous products. In addition, the microbial decomposition of roots, plant litter, and dung 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.

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 soil and air 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 pasture 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.

Pasture colour and growth relative to urine patches (p. 52)can provide an additional indication of the potential of the soil to sequester or lose C. First, poor growth and yellow pasture relative to urine patches indicate the N and S cycle has broken down because the amount of humus and the number and activity of soil organisms responsible for nutrient retention, turnover and supply have been degraded. The input of soil C declines as a consequence causing a net loss of C. Second, the strong growth of grass in the urine patches also indicates the dissolution and loss of a significant amount of C by the high concentration of N in the urine patch (see below).

Amount and form of fertiliser and nitrogen applied to pastoral soils (see scorecard, p. 89) 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, vermicasts, worm leachates, 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' conditioner 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 pasture management practices, good pasture production, pasture quality and soil C levels can be sustained and increased over the long term.

The plant converts CO_2 in the atmosphere into dissolved organic carbon (DOC, i.e. liquid sugar) by photosynthesis in the leaves of the plant. The dissolved liquid carbon is subsequently transported in the sap through the roots to the soil across a microbial 'bridge' formed by the mycorrhizal fungi. This provides a constant flow of C to the soil and at the same time feeds the microbes (mycorrhizal fungi and bacteria) attached to the roots and in the soil. The microbes in turn provide macro-nutrients (such as P, organic N and

Ca), trace elements (Zn, B, and Cu), and plant growth hormones to the plant in exchange for the sugar, a process known as ‘bidirectional flow’. The supply of nutrients stimulates plant growth, which in turn increases the photosynthetic supply of liquid C to the soil and soil microbes, increasing the population of soil microbes. Mycorrhizal roots can transfer as much as 15 times more carbon to the soil than can non-mycorrhizal roots. The DOC not used directly by the soil microbes is converted through the process of microbial humification to humus, which is a relatively stable form of carbon. Up to 80 percent of DOC can be humified if there is sufficient microbial diversity and the right fungal metabolites (including amino acids) and enzymes are present. Soil microbes, including actinomycetes and mycorrhizal fungi, also play an important role in the decomposition of organic matter to humus. Mycorrhizal fungi decompose organic matter to form glomalin, an important stable organic compound that can comprise 30 percent or more of the humus fraction in pastoral soils.

Mycorrhizal fungi and bacteria, include those forming the microbial bridge between the soil and the plant roots are strongly inhibited by excessive soil disturbance and high levels of water-soluble, salt-based forms of N and P. Cultivation and the application of high levels of mono-ammonium phosphate (MAP), di-ammonium phosphate (DAP), superphosphate, urea, and anhydrous ammonia suppress and disrupt the mycorrhizal colonization of plant roots and thus the microbial bridge, reducing the photosynthetic rate by up to 35 percent and, as a result, significantly reducing C flow to the soil and its humification to humus. Conversely, appropriately managed farmland promotes carbon sequestration by allowing the liquid carbon pathway to function.

Moreover, while nitrogen promotes pasture growth, and therefore the input of C into the soil, certain forms of N are more effective 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 C and carbohydrates such as humates (e.g., ammonium humate, humic/fulvic acids) than when using many other forms of N.

The application of frequent and high rates of soluble granular forms of N and high analysis nitrogenous fertilisers to boost dry matter production:

i) promotes the vegetative growth of the shoots relative to the roots and creates lazy plants, encouraging a shallow root system. The subsequent increase in the shoot:root ratio results in a significant reduction in C input into the soil because shoots contribute 6 times less C than roots do;
ii) produces ‘watery’ pasture with a lower dry matter content and a lower concentration of C in the shoots and roots, adding less C to the soil on decomposition;
iii) leads to 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 20:1 or less;

iv) causes the N enrichment of urine and the subsequent mineralisation of soil C by stimulating the activity of the microbial biomass through the priming action of dissolved carbon in the urine. As a result, bacteria mineralise 2–3 times the amount of humus they would ordinarily mineralise. High concentrations of N in urine patches may also cause the dissolution (emulsification) of soil humus and its subsequent loss as dissolved organic C in the leachate;

v) reduces the earthworm and microbial biomass, further reducing C levels in the soil.

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 pastures 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 (such as ammonium humate, humic/fulvic acids), and ensuring that Ca levels in the soil are good (with a Ca base saturation of 60–70 percent). The utilisation of N and its indirect conversion to soil C is further improved by promoting the amount of humus, soil life, potential rooting depth, root length density, and pasture growth.

The form in which essential elements are applied can also have a significant effect on carbon levels. For example, potassium sulphate is a biologically friendly form of potassium and, as such, increases pasture production and C flow to the soil, partly by providing a soil environment conducive to mycorrhizal activity and the formation of a microbial bridge between the roots and soil. Potassium chloride (muriate of potash), on the other hand, can be harmful to the roots and soil life, and can have adverse effects on animal health.

Moreover, 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.

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. ≤30), certain management practices and specific types of fertiliser and N (if required) need to be applied to increase the sequestration of C in the soil. Soils with a high Soil Carbon Index (>30) not only enable significant gains in profitability, including the potential for C credits, but also provide substantial environmental benefits as well.

Off-setting GHG emissions

The sequestration over a-12 month period of 6.3 and 7.1 tonnes C/ha in the top 1 m of soil (an increase of 3.6 and 5.5 percent respectively from the previous year) on two dairy farms that recently converted from soluble, salt-based high-analysis N:P:K fertilisers to bio-friendly fertilisers, equates to the sequestration of 23 and 26 tonnes CO_2 equivalents/ha respectively. GHG emissions from dairy farms are typically of the order of 7–9 tonnes CO_2 equivalents/ha/yr, two-thirds less than the 23–26 tonnes CO_2 equivalents/ha sequestered as soil C. The soil clearly has a huge capacity to act as a carbon sink under appropriately managed farmland, off-setting GHG emissions. Soil carbon sequestration by adopting carbon farming strategies, such as developing the root system, increasing earthworm numbers, and applying bio-friendly forms of fertilizer, is consequently a cost-effective strategy to mitigate GHG emissions.

Carbon sequestration of atmospheric CO_2 in the soil, ultimately as stable humus, may well provide a more lasting solution than temporarily sequestering CO_2 in the standing biomass through re- and afforestation. Carbon sequestration will also contribute to higher soil fertility, greater biodiversity, aeration, infiltration and water-holding capacity, less droughtiness and dependence on supplements in protracted dry periods, and sustainable food productivity and quality.

PLATE 52 **A carbon negative field**

1984

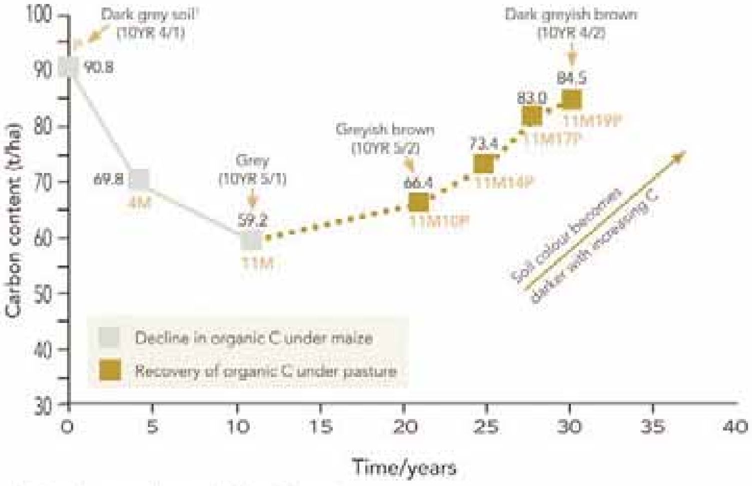
Total organic C declined in the upper 200 mm of soil from 90.8 tonnes/ha under pasture to 59.2 tonnes/ha after 11 years of maize under poor management practices (Figure 6). Photo taken in 1984 after harvesting for the 11th consecutive year of maize (for grain).

PLATE 53 **Carbon sequestration under pasture**

2008

Carbon sequestration under pasture following 11 yrs of continuous maize cropping. Total organic C recovered from 59.2 tonnes/ha under 11 yrs of maize to 84.5 tonnes/ha in the upper 200 mm of soil after 19 yrs of ryegrass/clover pasture, an average recovery rate of just 1.3 tonnes C/ha/yr (Fig. 6). The rate of C sequestration could have been much greater had pastoral management practices focused better on promoting soil life, the potential rooting depth, root length and root density, pasture production and pasture quality, and applied the appropriate amount and form of fertiliser and N.

FIGURE 6 **Rate of recovery of total C under pasture following intensive cropping**



1 Soil colour according to the Munsell notation

Total C in the topsoil (0–200 mm) and associated soil colour after 10, 14, 17 and 19 years of pasture following 11 yrs of maize under conventional cultivation.

FIGURE 7 **Scorecard – visual indicators to assess the potential for carbon sequestration**

Land owner:	**Land use:**	**Site:**	**GPS:**
Soil type:	**Drainage class:**	**Topsoil depth:**	**Date:**

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

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]) pg. 2		x 2	
Clay mineralogy (Scoring protocol is given below[2]) pg. 82		x 2	
Soil colour pg. 10		x 1	
Earthworms (Number =) (Av. size =) pg. 14		x 3	
Potential rooting depth (mm) pg. 22		x 3	
Root length and root density pg. 60		x 3	
Pasture growth pg. 50		x 3	
Pasture colour and growth relative to urine patches pg. 52		x 2	
Amount and form of fertilizer and N applied (Scoring protocol is given below[3])		x 3	
SOIL CARBON INDEX (sum of VS rankings)			

Soil Carbon Assessment	Soil Carbon Index
Soil is potentially carbon negative	< 16
Soil is potentially carbon neutral	16–30
Soil is potentially carbon positive	> 30

[1] **Textural group (Fig. 2b, p. 3): VS = 2** for Clayey; **VS = 1.5** for Fine loamy and Fine silty; **VS = 1.0** for Coarse silty and Peaty (virgin land); **VS = 0.5** for Coarse loamy; **VS = 0** for Sandy and Peaty (developed land). Strictly speaking, peaty soils cannot be defined as a textural group; however, they are closely aligned to, and have a huge effect on, soil texture.

[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' conditioner fertilisers are used, and N is applied as a foliar spray or in a carbon-friendly form in low amounts; or ≤ 30 kg N/ha/yr is applied as urea or in other forms of highly soluble, salt-based nitrogenous fertilisers; **VS = 1** if moderate amounts of highly soluble, non-biologically friendly salt-based phosphatic & potassic fertilisers are used, and 60–90 kg N/ha/yr is applied as urea or in other highly soluble, salt-based nitrogenous fertilisers; **VS = 0** if high amounts of highly soluble, salt-based phosphatic & potassic fertilisers are used, and > 120 kg N/ha/yr is applied as urea or in other highly soluble, salt-based nitrogenous fertilisers.

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

❶ Assess the potential of greenhouse gas (GHG) emissions from a site by transposing onto the GHG Emissions Scorecard (Fig. 9, p. 99) the visual scores (VS) for Textural group, Soil porosity, Soil mottles and Soil colour from the Soil Scorecard, and the visual scores for Pasture quality, Pasture growth, and Pasture colour and growth relative to urine patches from the Plant Scorecard. Also add a ranking score for stocking rate and the amount and form of nitrogen 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 methane and nitrous oxide and is responsible for 15 percent of greenhouse gas emissions worldwide. In an agriculture-based country like New Zealand, farming practices can produce half the country's GHG emissions, of which 33 percent is breathed out as CH_4 from the digestive system of the animal and from dung emissions, and 17 percent is emitted as N_2O from animal urine, dung and nitrogenous fertilisers. These high emission levels are more to do with farm-management practices than the farming of ruminant animals. Climate-friendly and smart agricultural management can significantly reduce emissions.

GHG emissions result from a number of sources, including the soil, stock, and applied fertiliser N. The level of emissions varies according to a number of factors, including the condition of the soil, the quality of the pasture, and the application of nitrogenous fertilisers, 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

PLATE 54 **Field with a low potential for greenhouse gas emission**

Field with a low potential to emit GHGs due to good pasture quality and the soil being a well-drained, coarse silty soil with good porosity. The stocking rate is moderately low, urine patches are not readily apparent and little water-soluble, salt-based nitrogenous fertilizer is applied. In addition, good pasture growth and cover removes a large amount of CO_2 from the atmosphere by photosynthesis and intercepts/absorbs a large amount of CO_2 escaping from the soil.

PLATE 55 **Field with a high potential for greenhouse gas emission**

Field with a high potential to emit GHGs due to poor pasture quality and the soil being an imperfectly drained, fine silty soil with poor porosity. The stocking rate is high, urine patches are strongly expressed, and high application rates of water-soluble, salt-based nitrogenous fertilizer are applied. In addition, poor pasture growth and cover removes only a small amount of CO_2 from the atmosphere by photosynthesis and intercepts/absorbs a small amount of CO_2 escaping from the soil.

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. Apart from improving soil quality, the C credits gained can off-set farmer's GHG emissions.

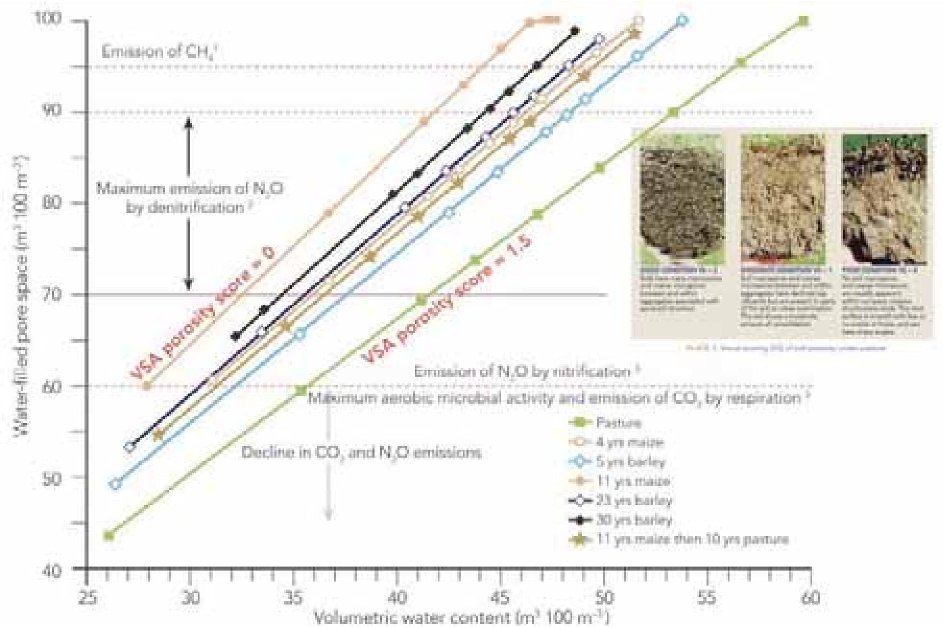
While CO_2 is a major GHG, it is reabsorbed as photosynthate by plants and can therefore be greenhouse neutral. Most atmospheric methane is also removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radical in the atmosphere. In addition, methane is inactivated by oxidation in aerated, biologically active soils (methanotrophy), and represents a globally significant sink. Nitrous oxide emissions, however, are more of an issue because their Global Warming Potential (i.e. a heat-absorbing ability) is 310 times that of CO_2 and, unlike CO_2 and CH_4, they do not have a natural means of regulating their levels in the atmosphere. While 70 percent of the total global N_2O is produced during denitrification, denitrifying bacteria and denitrification enzymes would have to achieve complete denitrification to emit N_2 instead of N_2O as an end product. Emphasis must therefore be placed on reducing the application of nitrogenous fertilisers and the emission of N from stock, and on promoting the many alternative pathways to supply N through biological processes (pp. 12, 14 & 20–21) and from legumes such as clovers (p. 44–45).

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

Textural groups (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. Finer textured (heavier) soils also tend to be more poorly drained and therefore more likely to emit GHGs, as discussed below. Soils with a peaty ‘textural’ group are high amitters of CO_2 and CH_4.

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. 8); 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. Soil compaction can cause a seven-fold increase in N_2O emissions.

FIGURE 8 **Effect 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.

A moderately well-structured soil under pasture with a VSA soil porosity score of 1.5 (see right hand graph in Fig. 8) 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 years of poorly managed maize cropping with a VSA soil porosity score of 0 (left hand graph in Fig. 8) 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 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. 8, 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. Emissions of N_2O can be 20 percent lower in a well-drained sandy loam soil than in a poorly drained silt loam soil. 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.

Pasture quality (p. 34) can provide an additional indication of the potential for GHG emissions. Poor quality pastures with high nitrate-N and crude protein levels, poor pasture composition, and low sugar (energy) levels are difficult for the microorganisms in the rumen of the animal to break down by fermentation. As a result these pastures have a low feed-conversion efficiency, producing high amounts of CO_2 and CH_4, which the animal emits through belching and flatulence. High N and low sugar levels in the pasture also markedly increase the concentration of N excreted in the urine and dung because the rumen microbes have insufficient energy to utilize the excess N in the feed, converting 80 percent of it into ammonia instead of into milk, meat and fibre. As a consequence, the high concentration of N in the urine, often equivalent to 1 000–1 600 kg N/ha, markedly increases the amount of N_2O emitted into the atmosphere. High nitrate, crude-protein pastures also cause an overly alkaline gut that results in scouring and the production of 'liquid' dung with high concentrations of N and CH_4 that are subsequently emitted into the atmosphere. In contrast, nutrient-dense, sugar-rich, high-quality pastures containing mature proteins, high levels of soluble non-structural carbohydrates, condensed tannins and cobalt, have a high metabolisable energy and digestibility. As a consequence, they have a high feed-conversion efficiency that produces significantly less CO_2 and CH_4 in the rumen and digestive tract. They also produce less N in the urine and less N and CH_4 in the dung, and therefore emit less GHGs. Condensed tannins can reduce CH_4 emissions by 15 percent, by decreasing methanogenesis. Moreover, high quality pastures shift the production of acetates (CH_3COOH) in the rumen to propionates (volatile fatty acids – CH_3CH_2COOH), leading to a reduction in hydrogen and consequently in the production of CH_4. Plants such as coriander and turmeric could reduce the amount of methane produced by bacteria in an animals stomach by up to 40 percent.

The concentration of N in the urine and GHG emissions is also reduced by ensuring the animal intake of Co in the herbage is adequate to enable the bacteria in the rumen to produce the vitamin B_{12} necessary to promote efficient digestion through good rumen function. To this end, Co levels in the herbage should be of the order of 0.1–0.15 mg/kg. Moreover, good rumen function and therefore greater feed-conversion efficiency (to build protein) and lower GHG emissions are improved by ensuring yttrium levels are adequate in the rumen.

Pasture quality also influences the volume of feed intake and thus the amount of GHGs emitted. Good quality pastures with high energy levels, nutrient density and nutritive value have a higher palatability and digestibility and contain more useful energy per unit of dry matter than poor quality pastures. Animals therefore need to eat less to attain the number of kilojoules required for body maintenance, growth, and lactation. As a result, the amount of forage digested is less, which reduces the level of GHGs emitted. The animal produces less dung and urine and consequently there are less CH_4 emissions from the dung and N_2O from the urine. Highly digestible forage also spends less time in the rumen thereby producing fewer fermentation gases, including CH_4 and CO_2. Animals grazing a ryegrass sward produce twice the amount of CH_4 (24 g/kg dry matter intake) compared with animals grazing white clover (12.9 g/kg dry matter intake). Methane emissions can be reduced by at least 10 percent when grass forage is replaced by a mixed ryegrass/legume sward.

While forage-fed ruminants can emit significant amounts of GHGs and as a result are often used as global warming scapegoats, in reality much can be done to significantly reduce their emissions. This can be achieved by improving the quality of advice given to farmers, including addressing the factors discussed above.

Pasture growth (p. 50) can provide an indication of the potential to reduce GHG emissions. The greater the pasture growth, 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 and the conversion of pasture into GHGs by grazing animals. As CO_2 escapes from the soil, most, if not all, is absorbed by the stomata on the leaves, which have an insatiable appetite for CO_2. The greater the pasture cover (leaf area index), the greater the amount of CO_2 removed. Furthermore, if we assume that one kilogram of carbon in the dry matter grown removes 3.67 kg CO_2 from the atmosphere, a farm growing 18 tonnes of dry matter/ha/year (or 7.4 t C/ha/yr) will remove approximately 27 tonnes of atmospheric CO_2/ha/yr. A farm growing just 15 tonnes of dry matter/ha/yr (or 6.2 t C/ha/yr) will remove approximately 23 tonnes of atmospheric CO_2/ha/yr, 15 percent less than the higher producing farm. While CO_2 is the least potent of the GHGs with a Global Warming Potential (i.e. a heat-absorbing ability) 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 carbon, is an effective and highly beneficial means of reducing its amount in the atmosphere.

Pasture colour and growth relative to urine patches (p. 52) can provide a further indication of the potential for GHG emissions. First, poor growth and yellow pasture between urine patches and strong pasture growth in the urine patches indicate poor quality pasture with low sugar levels and the subsequent emission of CH_4 and excretion of N-rich urine. The N gives rise to increased emissions of N_2O by the denitrification of nitrate and nitrification of ammonium present in high concentrations in the urine patches. Second, poor growth and yellow pasture between urine patches indicates the nitrogen and/or sulphur cycle has broken down, suggesting a decline in the uptake of N by the plant and its subsequent release to the environment.

The **amount and form of nitrogen applied** to the soil (see scorecard, p. 99) can provide another indication of the potential for GHG emissions. Nitrous oxide emissions from soils are caused principally by microbial nitrification and in particular by 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. 8). In addition to N added in the form of animal excreta, particularly as urine, the nitrification of urea and ammonium-based fertilisers, and the denitrification of high concentrations of nitrates in the soil resulting from the excessive application of other salt-based nitrogenous fertilisers, can provide a significant source of N_2O emissions. Increasing the application rate of urea from 80 to 190 kg N/ha, for example, can increase N_2O emissions from 1.2 to 3.6 t/ha (on a CO_2-equivalent basis).

The excessive use of nitrogenous products can also reduce the capacity of soils to take up and oxidise atmospheric CH_4, thereby reducing the ability of the soil to act as a methane sink. Aerobic soils can be net sinks for CH_4 due to the presence of methanotrophic bacteria that take up methane as their sole source of energy. Methanotrophs are however chemically sensitive, and their biomass and activity is reduced by nitrogenous and other soluble, salt-based inorganic fertilisers, the N inhibitor Dicyandiamide (DCD), herbicides, insecticides, acidification and excessive soil disturbance. Farming in ways that enhance rather than inhibit soil biological activity would improve the capacity of agricultural soil to act as a methane sink, helping to mitigate CH_4 emissions.

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 pastures 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 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/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 60–70 percent) 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 length and root density, and pasture 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 percent, 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. It can further produce phytotoxic effects and yield reductions in white clover. 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. 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 to reduce N loss.

Stocking rate (see scorecard – p. 99) can significantly influence GHG emissions. Nitrogen deposited in the form of animal urine and dung is a principal source of N_2O production in managed grazing systems (Plate 56). More than half New Zealand's N_2O emissions originate directly from excretal N in grazed pastoral soils, while another 30 percent of emissions are from indirect emissions from leached and volatilized excretal-N. Nitrous oxide emissions from soils are caused principally by microbial nitrification and especially denitrification, processes controlled partly by the concentration of mineral N (NH_4^+ and NO_3^-) in the soil. Animal urine contains a lot of nitrogen, with urine patches containing an equivalent of up to 1 000–1 600 kg N/ha. The amount of urine produced is roughly proportional to the animal liveweight. A 500-kg dairy cow produces 13–27 litres of urine/day, approximately seven times the amount of a 70-kg ewe, which produces 1.8–3.6 litres of urine/day (Table 10, p. 78). The actual amount of N in urine depends strongly on the amount and form of soluble, salt-based nitrogenous fertiliser applied, the amount, quality and type of feed consumed, and the efficiency of rumen function. A high stocking rate on crude protein/nitrate-rich pasture receiving high amounts of soluble salt-based fertiliser N will significantly increase N_2O emissions compared with low stocking rates.

About 96 percent of anthropogenic CH_4 (i.e. caused by humans) is emitted from ruminant animals by methanogenic fermentation in the gut. Methane is also produced by anaerobic fermentation of animal manure. Like N_2O, the greater the stocking rate on poor quality, crude protein/nitrate-rich pasture, the greater the emissions of CH_4. Most of the methane, however, is removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radicals in the atmosphere, and by methanotrophic oxidation in aerated, biologically active soils, producing a globally significant sink.

Animal liveweight per hectare instead of stock units is used to define stocking rates because of the difficulty of accurately reporting stock units for different classes of livestock, and at different times of the year in terms of their size, feed (energy) requirements, animal performance and farming systems. The average liveweight per animal for different stock classes is given in Table 10 (p. 78) and can be quickly used to calculate stocking rate (and feed-use efficiency), regardless of the class of livestock.

PLATE 56 **High stocking rate with >2 000 kg liveweight/ha**

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 Emission Trading Schemes. If the GHG Emission Index is ≤26, certain management practices and the fertiliser regime need to be considered to minimise GHG emissions. A GHG Emission Index of >26 provides significant environmental benefits because less GHGs would be emitted into the atmosphere. Farmer involvement is the key to reducing agricultural emissions of GHGs. The GHG Emissions Scorecard provides farmers with a simple, quick tool to help them mitigate the production of GHGs.

Off-setting GHG emissions. The sequestration over a-12 month period of 6.3 and 7.1 tonnes C/ha in the top 1 m of soil (an increase of 3.6 and 5.5 percent respectively from the previous year) on two dairy farms that recently converted from soluble, salt-based high-analysis N:P:K fertilisers to bio-friendly fertilisers, equates to the sequestration of 23 and 26 tonnes CO_2 equivalents/ha respectively. GHG emissions from dairy farms are typically of the order of 7–9 tonnes CO_2 equivalents/ha/yr, two-thirds less than the 23–26 tonnes CO_2 equivalents/ha sequestered as soil C. The soil clearly has a huge capacity to act as a C sink, mopping up most of the excess carbon being emitted into the atmosphere. Soil C sequestration can therefore more than off-set GHG emissions under appropriately managed farmland. Soil carbon sequestration by adopting carbon farming strategies, such as developing the root system, increasing earthworm numbers, and applying bio-friendly forms of fertilizer, is consequently a cost-effective strategy to mitigate GHG emissions.

Enhanced feed nutrition and sequestration of atmospheric CO_2 in the soil, ultimately as stable humus, may well provide a more lasting solution than temporarily sequestering CO_2 in the standing biomass through re- and afforestation. Improved feed nutrition and microbially active soils will also help reverse the processes of land degradation and thus contribute to higher soil fertility, greater biodiversity, aeration, infiltration and water-holding capacity, less droughtiness and dependence on supplements in protracted dry periods, and sustainable food productivity and quality.

FIGURE 9 **Scorecard – visual indicators to assess the potential for greenhouse gas emissions**

Landowner: **Land use:** **Site:**

Soil type: **Drainage class:** **Date:**

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

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 .		x 3	
Soil colour . 10		x 1	
Pasture quality . 34		x 2	
Pasture growth . 50		x 2	
Pasture colour and growth relative to urine patches .52		x 2	
Amount and form of N applied (Scoring protocol is given below[2]) . 6		x 2	
Stocking rate (Scoring protocol is given below[3]) . g		x 2	
GHG EMISSION INDEX (sum of VS rankings)			

GHG Emission Assessment	**GHG Emission Index**
High potential for GHG emissions	< 14
Moderate potential GHG emissions	14–26
Low potential for GHG emissions	> 26

[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 and Peaty. Strictly speaking, peaty soils cannot be defined as a textural group; however, they are closely aligned to, and have a huge effect on, soil texture.

[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 ≤ 30 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; **VS = 1** if 60–90 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers; **VS = 0** if ≥ 120 kg N/ha/yr is applied as urea or in highly soluble, salt-based nitrogenous fertilisers.

[3] **Stocking rate** – kg liveweight (Lwt) per ha
VS = 2 if the Lwt is ≤ 1000 kg (≤ 2 cows*)/ha; **VS = 1.5** if the Lwt is 1250 kg (2.5 cows)/ha; **VS = 1** if the Lwt is 1500 kg (3 cows)/ha; **VS = 0.5** if the Lwt is 1750 kg (3.5 cows)/ha; **VS = 0** if the Lwt is ≥ 2000 kg (≥ 4 cows)/ha. [* assuming a cow of 500 kg liveweight]

References

Shepherd, T. G. 2010. *Visual Soil Assessment – Field guide for Pasture*. 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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