FIELD GUIDE

VISUAL SOIL ASSESSMENT

Pastures

Graham Shepherd, *soil scientist*,
BioAgriNomics.com, New Zealand

Food and Agriculture Organization of the United Nations
Rome, 2010

Plates, figures, tables and parts of the text are reproduced from Shepherd, T.G. 2009. Visual Soil Assessment, Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country. Second edition. Horizons Regional Council, Palmerston North. 119 p.; under copyright © Horizons Regional Council and BioAgriNomics Ltd 2009.

ISBN 978-92-5-105941-8

Contents

List of tables

List of figures

List of plates

Acknowledgements

Text, photographs, plates, tables and figures are reproduced from the original publication: **Shepherd, T.G.** 2009. *Visual Soil Assessment. Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country*. 2nd edition. Horizons Regional Council, Palmerston North, New Zealand, 119 p. with permission from Horizons Regional Council and BioAgriNomics Ltd.

This publication is funded by FAO.

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 Soil Assessment

Introduction

The maintenance of good soil quality is vital for the environmental and economic sustainability of pastoral land. A decline in soil quality has a marked impact on canopy cover, tiller density, pasture growth, pasture quality, food quality, animal health, production costs, nutrient loss into the groundwater and waterways, carbon sequestration and green-house gas emissions. It can therefore have significant consequences for society and the environment. A decline in soil physical properties in particular takes considerable time and cost to correct. Soil physical properties control the movement of water and air into and through the soil, the ease with which roots penetrate the soil, the number, type and activity of soil organisms, and the availability and uptake of soil nutrients. Damage to the soil can change these properties and reduce plant growth, food quality and environmental outcomes, regardless of nutrient status. Safeguarding soil resources for future generations and minimizing the ecological footprint of pastoral agriculture is an important task for land managers.

Often, not enough attention is given to:

- the basic role of soil quality in efficient and sustained production;
- the effect of the condition of the soil on the gross profit margin;
- the long-term planning needed to sustain good soil/pasture and food quality;
- the effect of land management decisions on soil quality, plant performance, and environmental outcomes.

Soil type and the effect of management on the condition of the soil are important determinants of the productive performance and quality of pastures and have profound effects on long term profits. Land managers need reliable, quick and easy to use tools to help them assess the condition of their soils and their suitability for pasture grazing, and make informed decisions that will lead to sustainable land and environmental management. To this end, the Visual Soil Assessment (VSA) provides a quick and simple method to assess soil condition and plant performance. It can also be used to assess the suitability and limitations of a soil for pastoral agriculture. Scoring is out of 50: the higher the score, the better the condition of the soil and the performance of the plant. Soils with good VSA scores will, by and large, give the best production with the lowest establishment and operational costs.

In addition, the VSA provides a quick, low cost method for estimating the potential for nutrient loss into the groundwater and waterways, C sequestration, and the emission of green house gases.

The VSA method

While the name Visual Soil Assessment implies a focus on the soil, the method is equally about assessing both the soil and the plant. Visual Soil Assessment is based on the visual assessment of key soil 'state' and plant performance indicators of soil quality, presented on a score card. Soil quality is ranked by assessment of the soil indicators alone. Plant indicators require knowledge of the growing history of the pasture. This knowledge will facilitate the satisfactory and rapid completion of the plant score card. With the exception of soil texture, the soil and plant indicators are dynamic indicators, i.e. they are capable of changing under different management regimes and land use pressures. Being sensitive to change, they are useful early warning indicators of changes in soil condition and plant performance and as such provide an effective monitoring tool.

Plant indicators allow you to make cause-and-effect links between management practices and soil characteristics. By looking at both the soil and plant indicators, VSA links the natural resource (soil) with plant performance and farm enterprise profitability. Because of this, soil quality assessment is not a combination of the 'soil' and 'plant' scores; rather, the scores should be looked at separately, and compared.

Visual scoring

Each indicator is given a visual score (VS) of 0 (poor), 1 (moderate), or 2 (good), based on the soil quality and plant performance observed when comparing the soil and plant with three photographs in the field guide manual. The scoring is flexible, so if the sample you are assessing does not align clearly with any one of the photographs but sits between two, an in-between can be given, i.e. 0.5 or 1.5. Because some soil and plant indicators are relatively more important in the assessment of soil quality and plant performance than others, VSA provides a weighting factor of 1, 2, and 3. The total of the VS rankings gives the overall Soil Quality Index and Plant Performance Index for the site. Compare these with the rating scale at the bottom of the scorecard to determine whether your soil and plants are in good, moderate, or poor condition.

Placing the soil and plant scores side by side at the bottom of the plant indicator scorecard should prompt you to look for reasons if there is a significant discrepancy between the soil and plant indicators.

The VSA tool kit

The VSA tool kit (Plate 1) comprises:

- **A SPADE** (flat-faced) – to dig a soil pit and to take a 200-mm cube of soil for the drop shatter soil structure test;
- **A PLASTIC BASIN** (about 450 x 350 x 250 mm) – to contain the soil during the drop shatter test;
- **A HARD SQUARE BOARD** (about 260 x 260 x 20 mm) – to fit in the bottom of the plastic basin on to which the soil cube is dropped for the shatter test;
- **A HEAVY-DUTY PLASTIC BAG** (about 750 x 500 mm) – on which to spread the soil, after the drop shatter test has been carried out;

PLATE 1 **The VSA tool kit**

- **A KNIFE** (preferably 200 mm long) to investigate the soil pit and potential rooting depth;
- **A WATER BOTTLE** – to assess the field soil textural class;
- **A MAGNIFYING HAND LENS** – to assess the clover nodules;
- **A TAPE MEASURE** – to measure the sample depth, topsoil depth, and potential rooting depth;
- **A BRIX REFRACTOMETER AND GARLIC CRUSHER** – to measure the sugar content of pasture. Although the VSA method is designed to be instrument free, the refractometer is highly recommended;
- **A VSA FIELD GUIDE** – to make the photographic comparisons;
- **A PAD OF SCORECARDS** – to record the visual score (VS) for each indicator.

The procedure

When should it be carried out?

The test should be carried out when the soils are moist and suitable for grazing. If you are not sure, apply the ‘worm test’ (p. 70). For **silty soils**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to test. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to test.

Setting up

Time

Allow 40 minutes per site. For a representative assessment of soil quality, sample four sites over a 5 hectare area.

Reference sample

Take a small sample of soil (about 100 x 50 x 150 mm deep) from under a nearby fence or a similar protected area. This provides an undisturbed sample required in order to assign the correct score for the soil colour indicator. The sample also provides a reference point for comparing soil structure and porosity.

Sites

Select sites that are representative of the field. Avoid areas that may have had heavier wheel and stock traffic than the rest of the field, e.g., around ‘camp’ sites, water troughs and gateways, etc. Also avoid atypical small areas within the field, such as small hollows or mounds, areas adjacent to groves or lines of trees, filled in pits, etc. VSA can also be used to assess the compactive and pugging effects of these high traffic areas on soil quality. Always record the position of the sites for future monitoring if required.

Site information

Complete the site information section at the top of the score card. Then record any special aspects you think relevant in the notes section at the bottom of the plant indicators score card.

Carrying out the test

Initial observation
Dig a small hole about 200 x 200 mm square by 300 mm deep with a spade and observe the topsoil (and upper subsoil if present) in terms of its uniformity, including whether it is soft and friable or hard and firm. A knife is useful to help you assess this.

Take the test sample
If the topsoil appears uniform, dig out a 200-mm cube with the spade.
You can sample whatever depth of soil you wish, but ensure that you sample the equivalent of a 200-mm cube of soil. If, for example, the top 100 mm of the soil is compacted and you wish to assess its condition, dig out two 200 x 200 x 100 mm samples with a spade. If the 100–200 mm depth is dominated by a tillage pan and you wish to assess its condition, remove the top 100 mm of soil and dig out two 200 x 200 x 100 mm samples. Note that taking a 200-mm cube immediately below the topsoil can also give valuable information about the condition of the subsoil and its implications for plant growth and pasture/crop management.

The drop shatter test
Drop the test sample a maximum of three times onto the wooden square in the plastic basin. The number of times the sample is dropped and the height it is dropped from, depends on the texture of the soil, and the degree to which the soil breaks up, as described on pp. 2 and 3.

Systematically work through the score card, assigning a visual score (VS) to each indicator by comparing it to the photographs (or table) and description reported in the field guide.

The plant indicators

Many plant indicators cannot be assessed at the same time as the soil indicators. Ideally, the plant performance indicators should be observed at the appropriate time during the season. The plant indicators are scored and ranked in the same way as soil indicators: a weighting factor is used to indicate the relative importance of each indicator, with each contributing to the final determination of plant performance. The Plant Performance Index is the total of the individual VS ranking in the right-hand column of the scorecard.

Format of the booklet

The soil and plant scorecards are given in Figures 1 and 3, respectively, and list the key indicators required to assess soil quality and plant performance. Each indicator is described on the following pages, with a section on how to assess the indicator and an explanation of its importance and what it reveals about the condition of the soil.

"Despite mankind's lofty aspirations and many notable achievements, our survival depends on a six-inch layer of topsoil and the fact that it rains"

anonymous

FIGURE 1 **Soil scorecard – visual indicators for assessing soil quality under pasture**

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

Moisture condition: ☐ Dry ☐ Slightly moist ☐ Moist ☐ Very moist ☐ Wet

Seasonal weather conditions: ☐ Dry ☐ Wet ☐ Cold ☐ Warm ☐ Average

Visual indicators of soil quality		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Soil texture	pg. 2		x 3	
Soil structure	pg. 4		x 3	
Soil porosity	pg. 6		x 3	
Number and colour of soil mottles	pg. 8		x 2	
Soil colour	pg. 10		x 2	
Earthworms (Number =) (Av. size =)	pg. 14		x 3	
Soil smell	pg. 18		x 2	
Potential rooting depth (m)	pg. 22		x 3	
Surface ponding	pg. 26		x 3	
Surface relief	pg. 30		x 1	
SOIL QUALITY INDEX (sum of VS rankings)				

Soil Quality Assessment	Soil Quality Index
Poor	< 20
Moderate	20–35
Good	> 35

Assessment

❶ Take a sample of soil half the size of your thumb from the topsoil to assess the ***soil texture***. Take also a sample/s that is/are representative of the subsoil to assess the overall ***textural group*** of the soil profile.

❷ Wet the soil with water, kneading and working it thoroughly on the palm of your hand with your thumb and forefinger to the point of maximum stickiness.

❸ Assess the texture of the soil according to the criteria given in Table 1 by attempting to mould the soil into a ball and then squeezing it between the thumb and forefinger. With experience, a person can assess the texture directly by estimating the percentages of sand, silt and clay by feel, and the *textural class* obtained by reference to the textural diagram (Figure 2a). The *textural group* is obtained by comparing the position of the textural class in Figure 2a with Figure 2b (e.g., silt loam = fine silty).

There are occasions when the assignment of a textural score will need to be modified because of the nature of a textural qualifier. For instance, if the soil has a reasonably high content of organic matter, i.e. is humic with 17–29 percent organic matter, raise the textural score by one (e.g., from 0 to 1 or from 1 to 2). If the soil has a significant gravelly or stony component, reduce the textural score by 0.5.

Importance

SOIL TEXTURE defines the size of the mineral particles. Specifically, it refers to the relative proportion of the various size-groups in the soil, i.e. sand, silt and clay. Sand is that fraction that has a particle size 0.06 mm; silt varies between 0.06 and 0.002 mm, while the particle size of clay is < 0.002 mm.

Texture influences soil behaviour in several ways, notably through its effect on water retention and availability, soil structure, aeration, drainage, soil trafficability and workability, soil life, and the supply and retention of nutrients. Knowledge of both the textural class and potential rooting depth (see p. 22) enables an approximate assessment of the total water holding capacity of the soil, one of the major drivers of pasture production.

FIGURE 2 **Soil texture classes and groups**

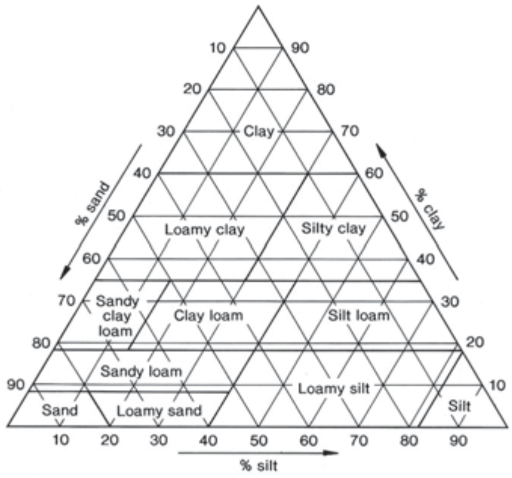


Figure 2a
Textural classes.

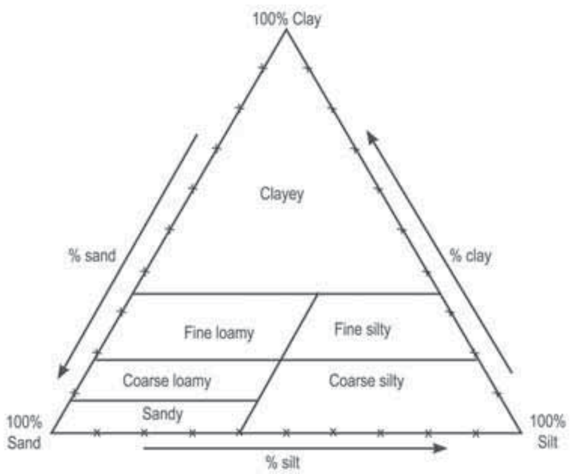


Figure 2b
Textural groups.

TABLE 1 **How to score soil texture**

Visual score (VS)	Textural class	Description
2 [Good]	Silt loam	Smooth soapy feel, slightly sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
1.5 [Moderately good]	Clay loam	Very smooth, sticky and plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
1 [Moderate]	Loamy silt Sandy loam	Smooth feel, non sticky, no grittiness. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger. Slightly gritty, faint rasping sound. Moulds into a cohesive ball which fissures when squeezed between thumb and forefinger.
0.5 [Moderately poor]	Silty clay & Clay	Very smooth, very sticky, very plastic. Moulds into a cohesive ball which deforms without fissuring when squeezed flat.
0 [Poor]	Loamy sand Sand	Gritty and rasping sound. Will almost mould into a ball but disintegrates when squeezed between thumb and forefinger Gritty and rasping sound. Cannot be moulded into a ball

Assessment

1. Remove a 200-mm cube of topsoil with a spade. When taking the sample, ensure the blade of the spade is inserted vertically to obtain the true volume of soil required for assessment.
2. Drop the soil sample a maximum of three times from a height of one metre onto the firm base in the plastic basin. If large clods break away after the first or second drop, drop them individually again once or twice. If a clod shatters into small (primary structural) units after the first or second drop, it does not need dropping again. Don't drop any piece of soil more than three times. For soils with a sandy loam texture (p. 2), drop the cube of soil once only from a height of 0.5 metres. If the sandy loam is humic (17–29 percent organic matter), drop the soil twice from 1 metre. Transfer the soil onto the large plastic bag.
3. For soils with a loamy sand or sand texture, drop the cube of soil still sitting on the spade once from a height of just 50 mm and then roll the spade over, spilling the soil onto the plastic bag.
4. Applying only very gently pressure, attempt to part each clod by hand along any exposed cracks or fissures if present. If the clod cannot be easily parted, do not apply further pressure because the cracks and fissures are probably not continuous and therefore unable to readily conduct oxygen, air and water.
5. Move the coarsest fractions to one end and the finest to the other end. Arrange the distribution of aggregates so that the height of the soil is roughly the same over the whole surface area of the bag. This provides a measure of the aggregate-size distribution. Compare the resulting distribution of aggregates with the three photographs and criteria given in Plate 2. The method is valid over a wide range of moisture conditions but is best carried out when the soil is moist to slightly moist; avoid dry and wet conditions.

Importance

SOIL STRUCTURE is important for pastures. It regulates soil aeration and gaseous exchange rates, soil infiltration and erosion, the movement and storage of water, soil temperature, root penetration and development, nutrient supply, and the resistance to structural degradation by compaction and deformation under wheel traffic and stock treading. Good soil structure improves the trafficability of the soil, increasing the window of opportunity for stock grazing and vehicle access without causing compaction. The loss of soil structure can alter seasonal growth patterns and change the botanical composition of pasture including an increase in the number of weeds. Structural degradation can reduce tiller density and canopy cover by 50 percent, pasture production by 30–50 percent in spring, and is often a catalyst for diseases. It also reduces the infiltration of water into and through the soil increasing the potential for erosion by sheet wash on sloping ground.

Soil structure is ranked on the size, shape, firmness, porosity and relative abundance of soil aggregates and clods. Soils with good structure have friable, fine, porous, sub-angular and sub-rounded (nutty) aggregates. Those with poor structure have large, dense, very firm, angular or sub-angular blocky clods that fit and pack closely together and have a high tensile strength.

PLATE 2 **Visual scoring (VS) of soil structure**

GOOD CONDITION VS = 2
Soil dominated by friable, fine aggregates with no significant clodding. Aggregates are generally sub-rounded (nutty) and often quite porous.

MODERATE CONDITION VS = 1
Soil contains significant proportions (50 percent) of both coarse clods and friable fine aggregates. The coarse clods are firm, sub-angular or angular in shape and have few or no pores.

POOR CONDITION VS = 0
Soil dominated by coarse clods with very few finer aggregates. The coarse clods are very firm, angular or sub-angular in shape and have very few or no pores.

Assessment

1. Remove a spade slice of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and break in half.
2. Examine the exposed fresh face of the sample for soil porosity by comparing against the three photographs and criteria given in Plate 3. Look for the spaces, gaps, holes, cracks, fissures between and within soil aggregates and clods.
3. Examine also the porosity of a number of the large clods from the soil structure test. This provides additional information as to the porosity of the individual clods (the intra-aggregate porosity).

Importance

SOIL POROSITY is important to assess along with soil structure. Soil porosity, and particularly macro porosity (or large pores), influence the movement of air and water in the soil. Soils with good structure have a high porosity between and within aggregates, but soils with poor structure may not have macropores or coarse micropores within the large clods, thus restricting their drainage and aeration.

Poor aeration leads to the build up of methane, sulphide gases and alcohol, and reduces the ability of plants to take up water and nutrients, particularly nitrogen, phosphorus, potassium, sulphur, zinc, copper and cobalt. Poorly aerated and compacted soils reduce plant-available nitrate-nitrogen (NO_3^--N) and ammonium (NH_4^+) to nitrite (NO_2^-), nitrogen (N_2) gas and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available sulphate-sulphur (SO_4^{2-}-S) is also reduced to sulphite (SO_3^{2-}) and sulphides, rendering N and S unavailable to the plant. Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can also only utilize N if S is present in the oxygenated sulphate form. Moreover, the number, activity and biodiversity of micro-organisms and earthworms are greatest in well-aerated soils and are able to decompose and cycle organic matter and nutrients more efficiently than in poorly aerated soils.

The presence of soil pores enables the development and proliferation of the superficial (or feeder) roots throughout the soil. Roots are unable to penetrate and grow through firm, tight, compacted soils, severely restricting the ability of the plant to utilise the available water and nutrients in the soil. A high penetration resistance not only limits plant uptake of water and nutrients, but greatly reduces fertiliser efficiency and increases the susceptibility of the plant to root diseases.

Soils with good porosity will also tend to produce less greenhouse gases. The greater the porosity the better the drainage and therefore the soil pores will be less likely to be water-filled to the critical levels required to generate the production of methane and nitrous oxide greenhouse gases (see pp. 92–93). Aim to keep the porosity score above 1.

PLATE 3 **Visual scoring (VS) of soil porosity**

GOOD CONDITION VS = 2
Soils have many macropores and coarse micropores between and within aggregates associated with good soil structure.

MODERATE CONDITION VS = 1
Soil macropores and coarse micropores between and within aggregates have declined significantly but are present in parts of the soil on close examination. The soil shows a moderate amount of consolidation.

POOR CONDITION VS = 0
No soil macropores and coarse micropores are visually apparent within compact, massive structureless clods. The clod surface is smooth with few or no cracks or holes, and can have sharp angles.

Assessment

1. Assess the number, size and colour of soil mottles by taking a sample of soil (approximately 100 mm wide × 150 mm long × 200 mm deep) from the side of the hole and comparing it with the three photographs and criteria given in Plate 4. The percentage chart below will help you determine the percentage of the soil occupied by mottles.

Mottles are patches of different colour interspersed within the dominant (background) soil colour.

Importance

The **NUMBER AND COLOUR OF SOIL MOTTLES** provide a good indication of how well the soil is drained and how well it is aerated. They are also early warnings of a decline in soil structure as a result of treading damage and compaction under wheel traffic. The loss of soil structure reduces the number of channels and pores that conduct water and air and, as a consequence, can result in waterlogging and a deficiency of oxygen for a prolonged period. The development of anaerobic (deoxygenated) conditions reduces iron (Fe) and manganese (Mn) from their *brown/orange* oxidised ferric (Fe^{3+}) and manganic (Mn^{3+}) form to grey ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Mottles develop as various shades of orange and grey due to varying degrees of oxidation and reduction of Fe and Mn. As oxygen depletion increases, orange, and ultimately grey mottles predominate. The abundance of grey mottles indicates the soil is poorly drained and poorly aerated for a significant part of the year. The presence of only common orange and grey mottles (10–25 percent) indicates the soil is imperfectly drained with only periodic waterlogging. Soil with only few to common orange mottles indicate the soil is moderately well drained, and no mottles indicate good drainage.

Poor aeration reduces the uptake of water by plants and can induce wilting. It can also reduce the uptake of plant nutrients, particularly N, P, K, S, Zn, Cu and Co (p. 6). Depending on soil type and soil condition, Olsen P levels of 22–35 mg/L are generally required for optimum pasture production. However, P levels need to be raised (sometimes to 40–50 mg/L) in compacted, poorly aerated soils to produce a positive dry matter production response. In addition, sulphur and nitrogen are reduced to plant-unavailable forms as described on the previous page. Moreover, poor aeration retards the breakdown of organic residues, and can cause chemical and biochemical reduction reactions that produce sulphide gases, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, which are toxic to plant roots. Root damage and reduced nutrient and water uptake give rise to poor pasture vigour. If your visual score for the number and colour of soil mottles is one or less, you need to aerate the soil.

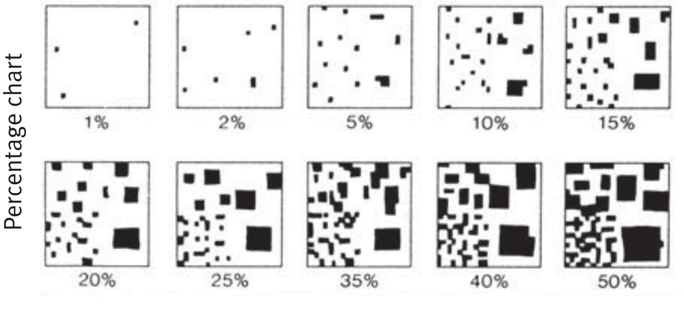


PLATE 4 **Visual scoring (VS) of the number and colour of soil mottles**

GOOD CONDITION VS = 2
Mottles are generally absent.

MODERATE CONDITION VS = 1
Soil has many (10–20 percent) fine and medium orange and grey mottles.

POOR CONDITION VS = 0
Soil has profuse (50 percent) medium and coarse orange and particularly grey mottles.

Assessment

❶ Compare the moist colour of a handful of soil from the field site with soil taken from under the nearest fenceline or a similar protected area (Plate 5). If the soil is dry, pour water over the surface of the sample.

❷ Using the three photographs and criteria given in Plate 6, compare the ***relative change*** in soil colour that has occurred. As topsoil colour can vary markedly between soil types, the photographs illustrate the degree of change in colour rather than the absolute colour of the soil.

Importance

SOIL COLOUR is a very useful indicator of soil quality because it can provide an indirect measure of other more useful properties of the soil that are not so easily and accurately assessed; in general, the darker the colour, the greater the amount of organic matter and humus in the soil. A change in colour can give a general indication of a change in organic matter under a particular land use or management. Soil organic matter plays an important role in regulating most biological, chemical and physical processes in soil, collectively determining soil health. It promotes infiltration, the movement and retention of water, helps develop and stabilise soil structure, cushions the impact of wheel traffic and stock treading, reduces the potential for wind and water erosion, plays a key role in maintaining the cation exchange and buffering capacity of the soil, and indicates whether the soil is

PLATE 5 **Soil colour under the fenceline**

Soil colour under the fenceline on the left compared with that in the field on the right. The comparative difference in soil structure and porosity is also a useful observation to make.

PLATE 6 **Visual scoring (VS) of soil colour**

GOOD CONDITION VS = 2
Dark coloured topsoil that is similar to, or darker than that under the fenceline.

MODERATE CONDITION VS = 1
The colour of the topsoil is somewhat paler than under the fenceline, but not markedly so.

POOR CONDITION VS = 0
Soil colour has become significantly paler compared with under the fenceline.

functioning as a carbon 'sink' or as a source of green-house gases. Organic matter acts as a major reservoir of organic carbon in the soil, carbon that is sequestered by microorganisms and from CO2 in the atmosphere by plants. Organic matter also provides an important food resource for soil organisms and is an important source and major reservoir of plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil; nitrogen, phosphorus, potassium and sulphur requirements of pastures increase markedly, and other major and minor elements are more readily leached. The result is an increased dependency on fertiliser input to maintain nutrient status.

Dark-coloured soils due to high amounts of organic matter and humus provide a major source of nitrogen and phosphorus. A soil with 1 percent organic carbon in the top 0–100 mm contains about 1 200 kg of organically bound N per ha. Over the course of a year, 1–5 percent of the organic N is mineralised by soil microorganisms to plant-available inorganic N in the form of ammonium (NH_4^+) and nitrate-nitrogen (NO_3^--N). A soil with 1200 kg N/ha can therefore potentially provide around 60 kg of plant available N/ha/yr. If we assume soils have an average organic C content of 5 percent, the activity of soil microbes can potentially supply 300 kg N/ha/yr. Ensuring a good, healthy, biologically active soil with average soil C levels can therefore provide the N requirements of a high-producing dairy farm. This is borne out by the fact that dairy farms with good soil life are commonly producing in excess of 17 tonne dry matter/ha/yr with no mineral N applied. Many soils have well in excess of 5 percent organic C in the top 0–100 mm and therefore hold greater amounts of organically bound N that could potentially become plant available. The key is to ensure that management practices, including the type and amount of fertilisers used, encourage rather than suppress the biological life of the soil and therefore the amount of available N present.

Soil colour (compared with that under the fenceline) can be a useful indicator of whether soils on a farm or in a field are becoming darker due to gaining (sequestering) carbon. If the soil is paler, it could possibly be losing carbon, i.e. becoming C negative. If there is no colour difference, the soil carbon regime may be in a steady (C neutral) state, i.e. neither losing nor gaining carbon. Soil colour, along with soil texture, clay mineralogy, earthworm numbers, root length and density, potential rooting depth, pasture growth (dry matter production), pasture colour and growth compared with urine patches, and the amount and form of fertiliser and N applied (see following pages) can collectively provide a clear indication whether a particular management practice or land use is carbon positive, neutral or negative. A farm that has similar or darker coloured topsoils in the field relative to the fenceline, with fine silty or clayey textures, good earthworm numbers, root length and density, potential rooting depth, pasture growth (dry matter production), pasture colour and growth relative to urine patches, and is applying carbon-friendly forms of fertiliser and N will sequester significant amounts of carbon (see carbon sequestration, pp. 80–89). The farm will therefore be C positive and in a position to potentially gain 'carbon credits' rather than possibly pay a carbon tax.

Soil colour can also be a useful indicator of soil drainage and the degree of soil aeration. In addition to organic matter, soil colour is markedly influenced by the chemical form (or oxidation state) of iron (Fe) and manganese (Mn). Very dark brown, brown, yellow-brown, reddish-brown and red soils without mottles indicate well-aerated, well-drained conditions where Fe and Mn occur in the oxidised form of ferric (Fe^{3+}) and manganic (Mn^{3+}) oxides. Grey-blue colours can indicate the soil is poorly drained or waterlogged and poorly aerated for long periods, conditions that along with low pH, reduce the form of Fe and Mn to ferrous (Fe^{2+}) and manganous (Mn^{2+}) oxides. Ferrous and manganous oxides are more soluble than their oxidised forms and are therefore more readily taken up by the plant. High levels of Fe and Mn in the soil and pasture suppress the availability of cobalt (Co), which in turn reduces the appetite of ruminant stock – as a consequence, stock lose condition.

In addition to the production of toxic levels of Fe^{2+} and Mn^{2+} ions, poor aeration and waterlogging gives rise to a further series of chemical and biochemical reduction reactions that produce toxins such as hydrogen sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde that damage the root system. This reduces the ability of plants to take up water and nutrients (particularly N, P, K, S, Zn, Cu and Co), causing poor pasture growth and vigour. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^{+} and K^{+} to be absorbed by the roots. As a result, pastures typically have low energy levels and are not as palatable because they are unable to take up nutrients such as Na that are necessary to make sugars.

What is more, soil colour can indicate the potential of a soil to convert plant-available forms of nutrients into unavailable forms. Soils that are distinctly grey in colour due to being anaerobic and waterlogged reduce plant-available N in the form of nitrate (NO_3^-) and ammonium (NH_4^+) to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas. Plant-available S in the form of sulphate-sulphur (SO_4^{2-}-S) is reduced to unavailable sulphides. Sulphur and nitrogen can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Plants also need S in the sulphate form to utilise N.

Dark coloured soils further suggest that the microbial biomass is predominantly aerobic, enabling the efficient decomposition of organic matter to humus and the retention, immobilisation and release of soil nutrients.

earthworms

Assessment

❶ Count the earthworms by hand, sorting through the soil sample used to assess soil structure (Plate 2, p. 5 & Plate 7). Note also the number of species present (Plates 8–10) and compare with the criteria given in Table 2. Earthworms vary in size and number depending on the species, maturity, and the season. For year-to-year comparisons, therefore, earthworm counts must be made at the same time of year (preferably late winter to early spring), and when soil moisture and temperature levels are good; avoid dry conditions. Earthworm numbers are reported as the number per 200-mm cube of soil. Earthworm numbers are commonly reported on a square-metre basis. As a 200-mm cube sample is equivalent to 1/25 square metre, the number of earthworms needs to be multiplied by 25 to convert to numbers per square metre.

Importance

EARTHWORMS provide a good indicator of the biological health and condition of the soil because their population density and species are affected by soil properties and management practices. Through their burrowing, feeding, digesting, and casting, earthworms have a major effect on the chemical, physical, and biological properties of the soil: they shred and decompose plant residue converting it to humus and releasing mineral nutrients. Compared with uningested soil, earthworm casts can contain 5 times as much plant available N, 3–7 times as much P, 11 times as much K, and 3 times as much Mg, characteristics that are due in part to the higher enzyme activity in the casts (see p. 20). They can also contain more Ca and plant-available Mo, and have a higher pH, organic matter, and water content. In addition, dead earthworms can contribute significant amounts of N to the soil, being 60–70 percent protein (dry weight) with a N content of 12 percent. Forty-five earthworms per 200-mm cube of soil (1 125/m^2) are roughly equivalent to a biomass of 4 tonnes of earthworm/ha, and could release 43–50 kg N/ha upon their death. The presence of earthworms also increases the mobilization of nitrate-N by 10 times and that of ammonium-N by 80 times, compared with soils without earthworms.

PLATE 7 **Sample for assessing earthworms**

Sample for assessing earthworms. Photo shows earthworms present in a 200-mm cube sample of soil.

PLATE 8 *Lumbricus rubellus*

A very active surface litter and dung feeding earthworm; commonly red-brown or red-purple in colour with a paler underside; has a distinctly flattened tail; commonly 25–220 mm long.

PLATE 9 *Aporectodea caliginosa*

A medium-sized (40–90 mm) topsoil dwelling earthworm; commonly grey-pink on both the dorsal and ventral surfaces; does not have a flattened tail.

PLATE 10 *Aporectodea longa*

A long (90–180 mm) deep burrowing earthworm; commonly dark grey-brown with a black head; tail end is paler and slightly flattened. Underside is paler than the dorsal surface.

Photos of *L.rubellus* and *A.caliginosa* – courtesy of Ross Gray, AgResearch Ltd.

TABLE 2 **Visual scores (VS) for earthworms**

Visual score (VS)	Earthworm numbers (per 200 mm cube of soil)
2 [Good]	≥ 45 (with preferably 3 or more species)
1.5 [Moderately good]	35–44
1 [Moderate]	25–34 (with preferably 2 or more species)
0.5 [Moderately poor]	15–24
0 [Poor]	< 15 (with predominantly 1 species)

Earthworms also act as biological aerators and physical conditioners of the soil, improving soil porosity, aeration, soil structure, soil aggregate stability, water retention, water infiltration, and drainage, and reducing surface runoff and erosion. They promote pasture growth by secreting plant-growth hormones and increasing root density and root development through the rapid growth of roots down nutrient-enriched worm channels. They also contribute to nitrogen fixation by promoting nitrogen-fixing microorganisms, nitrogen-fixing nitrogenase enzymes and the availability of Mo. While earthworms can deposit around 25–30 tonnes of casts/ha/yr on the surface (Plate 11), 70 percent of their casts are deposited below the surface of the soil. Earthworms can therefore have a major effect on the overall properties and condition of the soil.

Earthworms also increase the population, activity, and diversity of soil microbes. The number of beneficial bacteria can increase three-fold from 3 million per gram in soils with no worms to 10 million per gram after colonization by worms. Actinomycetes increase 6–7 times during the passage of soil through the digestive tract of the worm and, along with other microbes, play an important role in the decomposition of organic matter to humus and the supply of nutrients. Earthworms therefore play an important role in pastoral agriculture and can increase pasture production by 10–30 percent.

Earthworms can increase the depth of topsoil and the carbon content of both topsoil and subsoil by their burrowing, digesting, reworking, and mixing of soil and plant residues (bioturbation), and by the deposition of worm casts. High numbers of earthworms ingest considerable amounts of soil and plant material, building up soil C levels by converting C to more stable organic compounds bonded to clay particles. Organic matter gradually works down to the subsoil and so increases the depth of topsoil. The burrowing, casting, and incorporation of organic mater into the soil contributes to increasing topsoil depth by decreasing soil density and increasing the porosity, and therefore the volume of soil. Given that 30 percent of worm casts are deposited on the surface and 70 percent below ground, the potential for earthworms to increase soil carbon levels and topsoil depth is substantial. Deposition rates of soil at the surface due mainly to earthworm casts can vary from 2–20 mm/yr.

PLATE 11 **Surface of field 'boiling' with worm casts**

Earthworm numbers (and biomass) are governed by the amount of food available as organic matter and soil microbes, as determined by pasture production and the stocking rate. Their numbers are also governed by soil moisture, temperature, texture, soil aeration, pugging, legume content, pH, soil nutrients (including Ca), and the type and amount of fertiliser and nitrogen used. The over-use of acidifying salt-based fertilisers and ammonia-based products can reduce earthworm numbers.

PLATE 12 **Yellow-tail earthworm *(Octolasion cyaneum)***

Soils should have a good diversity of earthworm species with a combination of: (i) surface feeders that live at or near the surface to breakdown plant residues and dung; (ii) topsoil-dwelling species that burrow, ingest and mix the top 200–300 mm of soil; and (iii) deep burrowing species that pull down and mix plant litter and organic matter at depth.

Earthworm species can further indicate the overall condition of the soil. For example, significant numbers of yellow-tail earthworms (*Octolasion cyaneum* – Plate 12) can indicate adverse soil conditions.

Assessment

❶ Remove a spade slice of soil (approximately 100 mm wide × 100 mm long × 100 mm deep) and break in half. Place the exposed face of the soil close to your nose, take three deep sniffs, and compare with the criteria given in Table 3. Before sniffing the soil, place a tissue (or mask) over your nose to prevent the inhalation of any harmful microbes. The test is best carried out when the soil is moist, including during or immediately after the wet months of the year.

Importance

SOIL SMELL, while very dependent on the water content and aeration status of the soil, is also a good indicator of the amount and the activity of soil life and therefore soil health. Soil smell is determined principally by the gases given off by the aerobic or anaerobic respiration of soil microbes, and by the type and amount of organic matter and humus present in the soil. Aerobic respiration by soil fungi, bacteria, yeast, protozoa (i.e. single cell animals), nematodes, arthropods (mites, beetles, millipedes, etc.), and earthworms produce distinctive odours. The degree and nature of the odours are determined by the composition and activity of the soil biology which in turn is governed in part by the available food supply in the form of organic matter and humus. Soils rich in fungi, for example, produce aromatic compounds and organic acids that give an earthy, rich, sweet, fresh or sometimes musty smell. These are often the characteristic smells of forest soils, which are generally rich in fungi. The presence of similar fungal smells in a pastoral soil suggests it is not only well aerated but also has a good, active microbial biomass (Plate 14). This is because it must have large numbers of bacteria to maintain a fungal to bacteria ratio of 0.75:1 (or 1:1) that is necessary to preserve and promote pastoral plants. An imbalance of this ratio along with poor soil nutrition could explain why pastures may show poor persistence and a tendency to revert to other plant species such as woody weeds. Pastoral soils that are intensively grazed and fertilised tend to have a greater abundance of bacteria relative to fungi than soils that are less intensively grazed and fertilised. As a consequence, they are more

TABLE 3 **How to assess soil smell**

Visual score (VS)	Soil smell
2 [Good]	Soil has a distinct rich, earthy, sweet, wholesome or fresh smell.
1 [Moderate]	Soil has a slight earthy, sweet odour or a mineral smell.
0 [Poor]	Soil has a putrid, sour, chemical or unpleasant smell.

sensitive to stress such as droughts, are less efficient in terms of uptake, cycling and retention of nutrients including N, and are more susceptible to N leaching.

Biological regimes are sensitive to intensive land uses with the result that soils can have little or no soil smell. Anaerobic respiration of micro-organisms (including anaerobic bacteria and yeast) in saturated, poorly aerated soils produce methane and nitrous oxide (greenhouse gases), alcohol (ethanol and ethylene), acetaldehyde formaldehyde, and putrid sulphide gases including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS), all of which inhibit root growth when accumulated in the soil (Plate 15). Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

PLATE 13 **Sample to assess soil smell**

While soils should have good microbial biomass with levels preferably in excess of 1 800 mg/kg, and a good microbial quotient (i.e. the ratio of microbial biomass C to total organic C), to be beneficial, soil microbes also need to be active. The level of activity and therefore functionality of the microbial biomass is something that must always be kept in mind when assessing the status of the soil biological community. The activity and energy status of soil microbes can be assessed by measuring their respiration, the level of their respiration relative to their biomass (i.e. the respiration to biomass ratio or the metabolic quotient qCO_2), and their AEC, which should be 0.8. Microbial viability is maintained at AEC values between 0.8 and 0.5 – the cells die at values below 0.5.

Soil microbes, including actinomycetes and mycorrhizal fungi, 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 comprises up to 30 percent or more of the humus fraction in pastoral soils. Soil organisms also play a key role in the promotion and maintenance of soil fertility through nutrient and carbon cycling, and their role in the N and S cycle. Microbes immobilise and retain significant amounts of nutrients in the humus they produce and in their biomass, releasing them when they die. Moreover, soil microbes, including mycorrhizal fungi, play a major role in the supply of plant-available nutrients, digesting soil and fertiliser, and unlocking nutrients such as phosphorus that are fixed by the soil. Mycorrhizal fungi and bacteria provide a fundamentally important 'microbial bridge' that allows the bidirectional flow of liquid C (sugars) from the plant to the soil, and nutrients and plant growth hormones from the soil to the plant. High organic matter and microbial activity further result in a high level of activity of soil enzymes such as urease, protease, phosphatase and sulfatase, which result in a high turnover of N, P and S through the soil organic pool.

PLATE 14 **Soil with a moderately good smell**

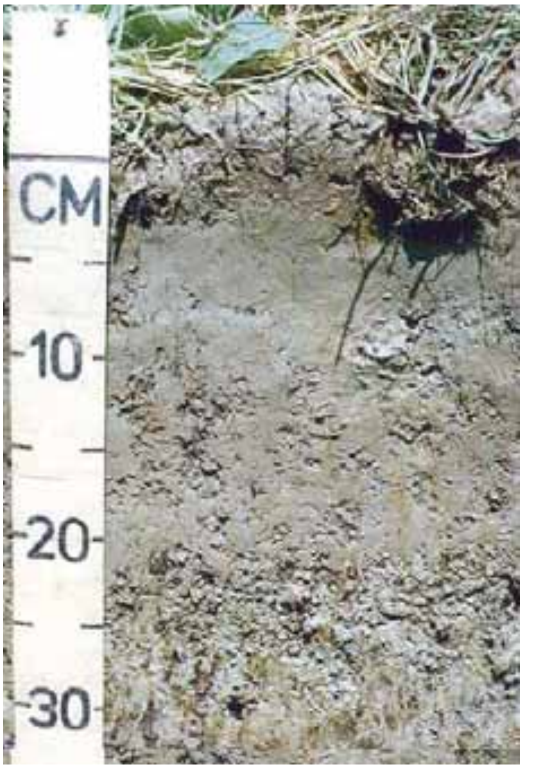
Soil has a moderately rich, earthy, sweet smell with a smell score of 1.5.

In addition, soil microbes and particularly bacteria play a major role in the fixation and supply of nitrogen. *Rhizobium* bacteria in clover nodules fix N directly from the atmosphere. The ammonia produced by N-fixation is taken up by the plant to produce protein and organic N compounds that are then mineralised by a further range of bacteria and fungi, releasing N in the form of plant available ammonium (NH_4^+) when the plant dies. Under aerobic conditions, the ammonium is converted by nitrosomonas and nitrobacter bacteria to nitrate (NO_3^-), another plant available form of N (a process known as nitrification). Free-living aerobic *Azotobacter* bacteria and anaerobic (*Clostridium*) bacteria in the soil further promote the fixation and supply of plant-available N.

Nitrogen fixing bacteria, be they free-living in the rhizosphere, confined to nodules on plant roots, or existing as endophytes in leaves or stems, derive most of their energy from dissolved organic carbon (liquid sugar) produced by photosynthesis. N-fixation is therefore very dependent on the flow of liquid carbon from the leaf to the roots. If plants are mycorrhizal, i.e. have high populations of mycorrhizal fungi and bacteria attached to the roots that form a microbial bridge between the plant and the soil, they don't require N in a mineralised form such as nitrate or ammonium. In order to transport mineralised N, mycorrhizal fungi have to convert it to glutamate, which represents an energy cost. For this reason, N is preferentially transported in an organic form, generally as amino acids such as glycine and glutamine.

Moreover, bacterial- and fungal-feeding protozoa and nematodes release large amounts of N when feeding on their selected prey and are responsible for much of the plant-available N in the majority of soils. The predator-prey interaction of protozoa on bacteria releases 5 units of plant-available N in the form of ammonium for every six bacteria consumed. The feeding of nematodes on bacteria releases 19 units of N for every 20 bacteria consumed. Given that bacterial numbers should be greater than one million per gram for all agricultural soils, and nearer 100 million per gram for productive soils, the potential storage and release of N from bacteria is considerable. Between 40 and 80 percent of the N in plants can come from the predator-prey interaction of protozoa with bacteria.

PLATE 15 **Soil with a poor smell**



Soil has a putrid, unpleasant smell of hydrogen sulphide with a smell score of 0.

In addition to adding organic matter to the soil, soil organisms play a key role in soil formation by developing and promoting the structure, aggregate stability, porosity, aeration, infiltration and water-holding capacity of the soil, and reduce waterlogging and runoff from the topsoil. Soil microbes also play an important role in purifying water and filter, buffer, degrade, immobilise, and detoxify organic and inorganic pollutants. Moreover, they suppress pests and diseases, producing compounds that inhibit the growth of, or are toxic to pathogens, reducing the invasion of the plant by a pathogen. Beauvaria fungi, for example, destroy the adult clover root weevil, providing an effective biological control. Soil microbes also produce plant growth hormones and compounds that stimulate root growth and produce B group vitamins, including vitamin B12 which is important for rumen function.

The collective benefits of microbes can reduce fertiliser requirements and more than double the growth of ryegrass and clover. They can also significantly improve the sugar content, nutrient density, and health of the plant. Soil life can therefore be effectively described as the ‘engine room’ of the soil, with mycorrhizal fungi being the powerhouse. The trick to smart and sustainable farming is to ensure the engine remains well oiled.

Assessment

❶ Assess the potential rooting depth by digging a hole to identify the depth to a limiting (restricting) layer if present, and compare with the class limits given in Table 4. As the hole is being dug, note the presence of roots and old root channels, worm channels, cracks, and fissures down which roots can extend. Note also whether there is an overthickening of roots (a result of a high penetration resistance), and whether the roots are forced to grow horizontally, otherwise known as right-angle syndrome. Moreover, note the firmness and tightness of the soil, whether the soil is grey and strongly gleyed due to prolonged waterlogging, and whether there is a hard pan present such as a strongly developed human-induced tillage or plough pan (p. 24), or a strongly developed natural pan such as an iron, silica or calcitic pan. An abrupt transition from a fine textured material to a coarse (sandy/gravelly) layer will also limit root development. A rough estimate of the potential rooting depth may be made by noting the above properties in a nearby road cutting or an open drain.

Importance

POTENTIAL ROOTING DEPTH is the depth of soil plant roots can potentially exploit before reaching a barrier to root growth, and indicates the ability of the soil to provide a suitable rooting medium for plants. The greater the rooting depth, the greater the available water-holding capacity of the soil, the greater the availability of soil nutrients, and the greater the resulting dry matter production. Fertilisers applied to pastures with deep rooting systems are more effectively utilised by the plant, resulting in less leaching of nutrients into the groundwater and waterways. During drought periods deep roots can access larger water reserves alleviating water stress and promoting the recovery and survival of the pasture. Conversely, soils with a restricted rooting depth due, for example, to a layer with a high penetration resistance (such as a compacted layer or a hardpan) limit uptake of water and nutrients, reduce fertiliser efficiency, increase leaching of nutrients, and limit pasture growth. A high resistance to root penetration can also increase plant stress and the susceptibility of the plant to root diseases. Moreover, hard pans impede the movement of air, oxygen and water through the soil profile, the latter increasing the susceptibility to waterlogging and erosion by rilling and sheet wash.

The potential rooting depth can be restricted further by:

- an abrupt textural change;
- low pH;
- aluminium (Al) toxicity;
- nutrient deficiencies;
- salinity;
- sodicity;
- a high or fluctuating water table;
- low oxygen levels.

Anaerobic (anoxic) conditions due to deoxygenation and prolonged water-logging restrict the rooting depth as a result of the accumulation of toxic levels of hydrogen sulphide, ferrous sulphide, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, by-products of chemical and biochemical reduction reactions.

Pastures with a deep, vigorous root system help to raise soil organic matter levels and soil life at depth, thereby contributing to the sequestration of C in the soil. The physical action of the roots and soil fauna and the glues they produce, promotes soil structure, porosity, water storage, aeration and drainage at depth. The presence of nitrogen-fixing clover root nodules at depth also encourages the further development of the root system by suppling nitrogen. A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Pastures are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up, so reducing losses by leaching into the environment.

PLATE 16 **Potential rooting depth**

Photo: Courtesy of Aaron Topp

Hole dug to assess the potential rooting depth.
Photo showing good potential rooting depth with abundant fine roots extending beyond the bottom of the photo at 810 mm depth.

TABLE 4 **Visual scoring (VS) of potential rooting depth**

VSA score (VS)	Potential rooting depth (mm)
2.0 [Good]	800
1.5 [Moderately good]	600–800
1.0 [Moderate]	400–600
0.5 [Moderately poor]	200–400
0 [Poor]	< 200

Identifying the presence of a hardpan

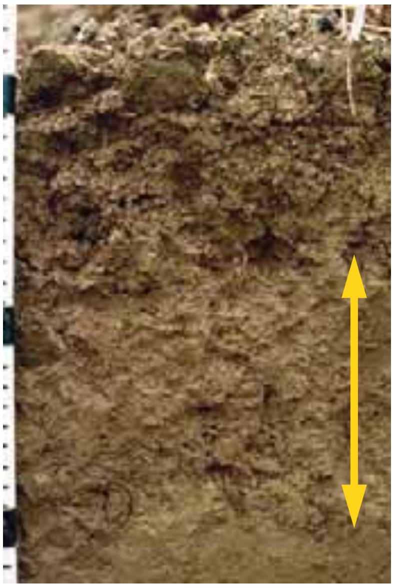
Assessment

1. Examine for the presence of a strongly developed hard pan by rapidly jabbing the side of the soil profile (dug to assess the potential rooting depth) with a knife, starting at the top and progressing systematically to the bottom of the hole (Plate 17). Note how easy or difficult it is to jab the knife into the soil as you move rapidly down the profile. Pay particular attention to the lower topsoil and upper subsoil where tillage pans and plough pans commonly occur if present (see photos below).
2. Having identified the possible presence of a hard pan by a significant increase in penetration resistance to the point of a knife, gauge how strongly developed the hard pan is. A strongly developed hard pan is very tight and extremely firm and has a high penetration resistance to the knife. Confirm also its presence or absence by removing a large, hand-sized sample and assess its structure, porosity and the number and colour of soil mottles (by referring back to pp. 4, 6 and 8). In addition, look for the presence or absence of roots. Compare with the photos and criteria given in Plate 18. Only a strongly developed hardpan will restrict all root development and its presence will determine the potential rooting depth.

PLATE 17 **Identifying the presence or absence of a hardpan with a knife**

PLATE 18 **Visual assessment of a hard pan**

NO HARDPAN
The soil has a low penetration resistance to the knife. Roots, old root channels, worm channels, cracks and fissures may be common. Topsoils are friable with a readily apparent structure and have a soil porosity score of ≥ 1.5.



MODERATELY DEVELOPED HARDPAN
The soil has a moderate penetration resistance to the knife. It is firm (hard) with a weakly apparent soil structure and has a soil porosity score of 0.5–1. There are few roots and old root channels, few worm channels, and few cracks and fissures. The pan may have few to common orange and grey mottles. Note the moderately developed tillage pan in the lower half of the topsoil (arrowed).

STRONGLY DEVELOPED HARDPAN
The soil has a high penetration resistance to the knife. It is very tight, extremely firm (very hard) and massive (i.e. with no apparent soil structure) and has a soil porosity score of 0. There are no roots or old root channels, no worm channels or cracks or fissures. The pan may have many orange and grey mottles. Note the strongly developed tillage pan in the lower half of the topsoil (arrowed).

surface ponding

Assessment

1. Assess the degree of surface ponding based on your observation or general recollection of the time ponded water took to disappear after a wet period during the autumn, spring and summer, and compare with the three photographs and criteria given in Plate 19.

Importance

SURFACE PONDING and the length of time water remains on the surface can indicate the infiltration rate into and through the soil, a high water table, and the time the soil remains saturated. Roots need oxygen for respiration, and prolonged waterlogging depletes oxygen in the soil, causing anaerobic (anoxic) conditions that induce root stress and restrict root respiration and growth. Roots are most vulnerable to surface ponding and saturated soil conditions in the spring when respiration and transpiration rates rise markedly, oxygen demands are high, and plant roots and shoots are actively growing. Such waterlogging causes the death of the fine roots responsible for nutrient and water uptake. Roots are also susceptible to ponding in the summer when transpiration rates are highest – reduced water uptake while the pasture is actively transpiring causes leaf desiccation and the wilting of plants.

Waterlogging causes pasture growth to decline due to poor shoot growth, fewer tillers, poor plant vigour, and chlorosis. In addition, pasture utilisation is reduced as a result of poor palatability, which is a function of:

- a change in pasture composition;
- deficiency in nutrients and sugars/carbohydrates;
- pasture becoming unpalatable and inaccessible by being soiled and trampled into the mud.

Prolonged waterlogging can change the composition of the pasture by stressing the less water-tolerant species and encouraging the development of undesirable water-tolerant species such as pennyroyal, duckweed, buttercup, etc. Prolonged waterlogging also increases root rot and soil-borne pathogens and limits the ability of roots to overcome the harmful effects of pathogens resident in the topsoil.

PLATE 19 **Visual scoring (VS) of surface ponding**

GOOD CONDITION VS = 2
No surface ponding of water evident after 1 day[1] following heavy rainfall on soils that were at or near saturation.

MODERATE CONDITION VS = 1
Moderate surface ponding occurs for 3–5 days[1] after heavy rainfall on soils that were at or near saturation.

POOR CONDITION VS = 0
Significant surface ponding occurs for longer than 7[1] days after heavy rainfall on soils that were at or close to saturation.

[1] Assuming little or no air is trapped in the soil at the time of ponding.

Waterlogging and deoxygenation result in a series of undesirable chemical and biochemical reduction reactions, the by-products of which are either toxic to roots or are in a form that is unable to be taken up by the plant, e.g.:

- iron is reduced to soluble ferrous (Fe^{2+}) ions and Mn to manganous (Mn^{2+}) ions;
- plant-available nitrate-nitrogen (NO_3^--N) is reduced by denitrification to nitrite (NO_2^-) and nitrous oxide (N_2O), a potent greenhouse gas;
- plant-available sulphate-sulphur (SO_4^{2-}-S) is reduced to unavailable sulphite (SO_3^{2-}) and sulphides, including hydrogen sulphide (H_2S), ferrous sulphide (FeS), and zinc sulphide (ZnS).

Sulphur (S) and nitrogen (N) can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form and therefore plants require aerated soils for the efficient uptake and utilisation of S and N. Furthermore, plants can only utilize N if S is present in the oxygenated sulphate form.

In addition to N and S, waterlogging and poor aeration reduces the availability and uptake of P, K, Zn, Cu, and Co. This is partly because prolonged ponding of water kills off mycorrhizal fungi, soil organisms that facilitate the efficient uptake and utilisation of soil nutrients, and P in particular. While Olsen P levels of 22 mg/L are generally adequate for optimum pasture production on most soils in good condition, poorly aerated and waterlogged soils with relatively high Olsen P levels (40–50 mg/L) can show a positive pasture response to applied P. Furthermore, the concentration of divalent cations such as Ca^{2+} and Mg^{2+} increases towards the exchange surface of the roots during prolonged soil wetness, thus reducing the ability of the monovalent cations such as Na^+ and K^+ to be absorbed by the roots. As a result, pastures typically have low energy levels and are not as palatable because they are unable to take up nutrients such as Na that are necessary to make sugars.

Anaerobic respiration of micro-organisms in waterlogged and poorly aerated soils produces methane (greenhouse gases), hydrogen gas, alcohol (ethanol and ethylene), acetaldehyde, and formaldehyde, all of which inhibit root growth when accumulated in the soil. Unlike aerobic respiration, anaerobic respiration releases insufficient energy in the form of adenosine triphosphate (ATP) and adenylate energy charge (AEC) for microbial and root/shoot growth.

The by-products of anaerobic respiration and the lack of oxygen in poorly aerated and waterlogged soils also prevent the decay of organic material in the soil. As the soil becomes progressively degraded, the amount of CO_2 increases relative to O_2 and reaches a point where plant residues cannot decay; instead they begin to ferment, producing alcohol, formaldehydes and methane, which make proper decay and the turnover of organic matter impossible.

Prolonged surface ponding increases the susceptibility of soils to damage by wheel traffic and stock treading, reducing vehicle access, trafficability, and grazability by stock. Waterlogged topsoils on sloping ground are also prone to erosion by sheetwash and sloughing, the latter process caused by the physical shunting of soil downslope brought about through the treading effect of stock. Soils susceptible to surface ponding therefore need to be carefully managed to minimise the effects of such ponding on soil, pasture growth, utilisation and quality, and the environment.

The tolerance of the root system to surface ponding and waterlogging depends on a number of factors, including the pasture species and the time of year. Tolerance of waterlogging also depends on soil and air temperatures, soil type and condition, fluctuating water tables, and the rate of onset and severity of anaerobiosis (or anoxia), a factor governed by the initial soil oxygen content and the oxygen consumption rate of plant roots.

Assessment

❶ Observe the surface relief (smoothness) of the paddock at the end of the winter and compare it with the three photographs and criteria given in Plate 20.

Although soils are most susceptible to treading damage (pugging) during wet winter months, observations of surface relief at any time of the year will give useful information on damage caused by past grazing and its likely effects on soil quality.

Importance

SURFACE RELIEF shows the severity of pugging under stock treading, and can indicate structural damage below the surface. Wet soils can pug severely under intensive grazing by heavy weight animals when the load-bearing capacity of the soil is insufficient to support the weight of the animal. This damages the soil structure and reduces the pores in the soil, which are important for water, nutrient and air movement, and root penetration. Infiltration rates and the movement of water through the soil decreases, increasing runoff, soil erosion, and the risk of flash flooding. Very broken and deeply incised soil as a result of severe pugging can also damage the pasture root system and increase the area of bare ground. It can further induce surface ponding and anaerobic conditions, reducing pasture utilisation and impairing pasture growth as a result of poor shoot growth, fewer tillers and poor plant vigour (see p. 26). In addition, the decay and turnover of organic matter is impaired by the production of methane, alcohol and aldehydes as described on p. 19.

PLATE 20 **Visual scoring (VS) of surface relief**

GOOD CONDITION VS = 2
Surface is relatively smooth and unbroken.

MODERATE CONDITION VS = 1
Surface terrain is somewhat broken up and incised by occasional heavy treading events but it is not difficult to walk over.

POOR CONDITION VS = 0
Surface is very broken and deeply incised by severe repeated treading. The terrain is difficult to walk across and care must be taken to avoid twisting ankles.

FIGURE 3 **Plant scorecard – visual indicators to assess plant performance in pasture**

Visual indicators of plant performance		Visual score (VS) 0 = Poor condition 1 = Moderate condition 2 = Good condition	Weighting	VS ranking
Pasture quality (Brix=)	pg. 34		x 3	
Clover nodules	pg. 42		x 3	
Weeds	pg. 46		x 2	
Pasture growth	pg. 50		x 3	
Pasture colour and growth relative to urine patches	pg. 52		x 3	
Pasture utilisation	pg. 58		x 3	
Root length and root density	pg. 60		x 3	
Area of bare ground	pg. 62		x 2	
Drought stress	pg. 64		x 2	
Production costs to maintain stock-carrying capacity	pg. 66		x 1	
PLANT PERFORMANCE INDEX (sum of VS rankings)				

Plant Quality Assessment	Plant Quality Index
Poor	< 20
Moderate	20–35
Good	> 35

SUMMARY

Comparison of soil & plant scores		Do the soil and plant scores differ? If so, why?
Soil indicators	Plant indicators	

Notes:

Total available water-holding capacity:

Assessment

❶ Assess the amount of green grass leaf, legume and dead matter (using the percentage chart on p. 36), and the botanical composition of the pasture during the time of year when pasture growth is strong due to favourable moisture and temperature conditions, and compare with the photographs and criteria given in Plate 21. Also measure the Brix (sugar) content of the pasture during the middle part of a sunny day using a simple refractometer. While not essential, measuring the Brix level is highly recommended.

In making the assessments, consider the original sowing mix, grazing management, competition and shading by other plants, fertiliser regime, and seasonal climatic conditions including air temperature and sunlight. Note there is a tendency to overestimate the amount of clover and underestimate the amount of dead matter.

Importance

PASTURE QUALITY varies according to the amount of green leaf and grass stem, legume content, dead matter, botanical composition, and sugar (energy) content of the pasture. While the stem is often considered to be lower quality than the leaf, it can have high concentrations of carbohydrates. Dead material has a very low nutritive value. Although pasture quality is governed by a number of factors, it can be a good indicator of the condition of the soil.

Pasture species is governed in part by the fertility of the soil and whether the plant is a high, moderate or low fertility species. High fertility species include perennial and Italian ryegrass, tall and meadow fescue, prairie grass, timothy, phalaris and white clover. Moderate fertility species include cocksfoot, crested dogstail, Yorkshire fog, sweet vernal, Kentucky bluegrass, creeping bent, and brome. Low fertility species include browntop, Chewing's fescue, paspalum, ratstail, danthonia, goosegrass, hairgrass, and needlegrass.

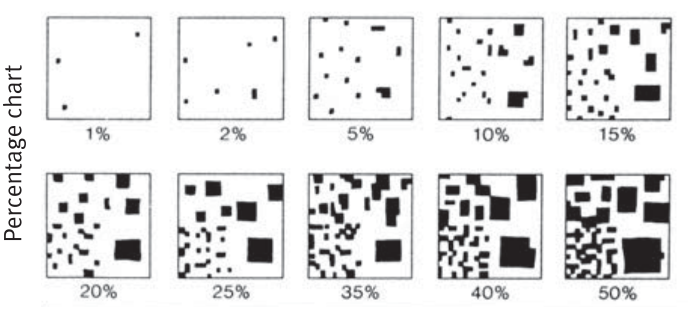
Pasture species also vary in their tolerance to poor soil aeration, pugging, soil and air temperatures, and moisture stress due to either waterlogging or a moisture deficit. Consequently, their nitrogen and sulphur uptake, dry matter production, and survivability also vary markedly. *Phalaris aquatica*, tall fescue, meadow fescue, meadow foxtail, Yorkshire fog, *Poa trivialis*, timothy, creeping bent, sweet grass, pennyroyal, waterpepper, buttercup, duckweed, and dock are tolerant of poor aeration and waterlogging due to pugging or poor drainage. Perennial ryegrass, white clover, cocksfoot, chewing fescue, browntop, *Poa annua*, and crested dogstail are moderately tolerant of poor aeration and waterlogging. Matua prairie grass, sweet vernal, *Poa pratensis*, ratstail, meadow rice grass, and yarrow are sensitive to poor aeration and waterlogging and will die out if conditions persist.

PLATE 21 **Visual scoring (VS) of pasture quality**

GOOD CONDITION VS = 2
Pasture has ≥ 95 percent green leaf herbage with ≥ 60 percent legume cover (≥ 30 percent DM), and < 5 percent dead matter. Brix sugar levels are ≥ 12.
Pasture composition has a good mix of high-producing pasture species (e.g., ryegrass, white clover, cocksfoot, etc.) and species intolerant of poor aeration and waterlogging (see below). Pasture composition reflects the original mix. Forage herbs including chicory, plantain and yarrow also contribute to pasture quality.

MODERATE CONDITION VS = 1
Pasture has 75–80 percent green leaf herbage with 20–40 percent legume cover (10–20 percent DM), and 20–25 percent dead matter. Brix sugar levels are 6–9.
Pasture composition has a mix of high and low fertility species. Pastures also show a range of tolerances to waterlogging and stock treading (see below). Pasture mix differs somewhat from that originally sown.

POOR CONDITION VS = 0
Pasture has < 50 percent green leaf herbage with little or no legume, and ≥ 50 percent dead matter. Brix sugar levels are ≤ 3.
Pastures are dominated by low- producing, low-fertility species and species that are more tolerant of poor aeration and waterlogging due to pugging; species such as ryegrass that are more tolerant of stock treading; and species such as white clover that quickly colonise bare ground created by severe treading (see below). Pasture composition has little relationship to the original seed mix.



Pasture composition will also change according to the degree of treading damage. Ryegrass and *Poa pratensis* resist treading damage better than many other species, and often become more common in pugged pastures. *Poa trivialis*, brown top, white clover, and timothy are moderately tolerant of treading. Cocksfoot, red clover, Yorkshire fog, and many low fertility pasture species such as sweet vernal and chewing fescue are sensitive to intensive treading and disappear under prolonged pugging. Treading damage and the exposing of bare ground will also allow the invasion by opportunist species such as white clover and *Poa annua*, broadleaf dock and other weeds, and less desirable pasture species. White clover, being stoloniferous, can rapidly colonise bare ground and become dominant in severely pugged pasture.

The importance of pasture quality

While the quantity (intake) of pasture is important in terms of stocking rate and animal performance, maximising pasture quality provides dramatic increases in overall farm profitability and environmental performance. The quality of the pasture has a major effect on conception and survival rates, live-weight gain, animal health, wool and milk production, and food quality. Quality pasture maximises the feed conversion factor into milk solids and meat thereby maximizing the dollar return per kg of dry matter consumed.

White clover contains more crude protein (or total N) and readily fermentable carbohydrates, but lower concentrations of water soluble carbohydrates (sugars), lipids, lignin, cellulose and fibre than perennial ryegrass. With the exception of Italian, tetraploid and hybrid diploid (high sugar) ryegrasses, which have higher soluble carbohydrate levels compared with many perennial ryegrasses, grasses often have similar nutrient levels under similar soil fertility, regardless of species. Legumes and herbs, on the other hand, have a higher nutritive value and feed quality than grasses, especially in summer when temperatures are higher. Legumes such as clover contain more Ca, P, Mg, Zn, Cu, B and Co, but lower concentrations of Na and Se than perennial ryegrass. Yarrow has significantly higher concentrations of P, K, Fe, Mn, Cu, B, Co and I than mixed ryegrass/white clover, and explains why lambs kill-out heavier when grazing paddocks containing yarrow. Chicory is higher in K, Na, Zn and Mo than ryegrass, and plantain is higher in Ca, Na, Fe, B, Co, Se, I and tannins than mixed ryegrass/white clover.

Condensed tannins (CT) in temperate pastures protect plant protein from digestion in the rumen, which results in a greater supply of protein to the small intestine, thus improving protein adsorption and animal performance in terms of live-weight gain, wool production, and reproductive efficiency. CTs also help protect ruminants against bloat, reduce the level of scouring and dags when grazing protein-rich pastures, reduce methane emissions by 15 percent by decreasing methanogenesis, and have a direct negative effect on internal parasites. Pastures containing birdsfoot trefoil (*Lotus corniculatus*), plantain and dock contain the most desirable forms of CTs, while the CTs in sainfoin, lotus major and sulla seem only to mitigate the impact of parasites. CT levels in pastures are generally low, and raising their concentration would improve pasture quality.

Pastures with a high energy level, nutrient density, and nutritive value have a higher palatability and digestibility and contain more useful energy per unit of dry matter. They also maintain good microbial growth rates and an active bacterial population in the rumen. Animals therefore have a higher feed-conversion efficiency and eat less to attain the number of kilojoules required for body maintenance, growth and lactation. Pasture quality also influences feed intake because while the animal wants to eat more herbage of low nutritive value to correct mineral imbalances, it moves more slowly through the animal's digestive track, physically restricting intake.

Pastures rich in crude protein and nitrate-N and with a low sugar content are difficult for the micro-organisms in an animal's rumen to break down by fermentation because of the lack of energy (sugars) in the pasture. Crude protein/nitrate-rich pastures also produce large amounts of nitrite (NO_2^-) that accumulates in the rumen during the reduction of nitrate (NO_3^-) to ammonia (NH_3). Nitrite reduces the total microbial population and, in particular, three of the four bacteria commonly found in the rumen. As a consequence, digestibility is reduced and livestock are only able to convert about 20 percent of the protein in the herbage into milk, meat and fibre – a low feed-conversion efficiency. Furthermore, because of the low sugar levels and high nitrate concentration, rumen microbes do not have the energy or capacity required to utilize the excess N in the feed and, as a consequence, convert 80 percent of it into ammonia. Some of the ammonia is used by the rumen bacteria for their own growth while most is absorbed into the blood stream. High concentration of ammonia in the blood (a toxic substance) overloads the liver as it attempts to convert it to urea, which is subsequently excreted in urine, milk and breath – this comes at a high energy cost to the animal. The bile ducts can also become blocked, forcing yellow bile out between the forelegs of the animal. The high concentration of N in the urine markedly increases the amount of N leached into the groundwater and waterways (pp. 75 & 76) and the amount of nitrous oxide (N_2O) emitted into the atmosphere (pp. 94–97). Poor rumen function also produces higher amounts of carbon dioxide (CO_2) and methane (CH_4). Moreover, pasture with poor digestibility spends more time in the rumen, thereby producing more fermentation gases, including CH_4 and CO_2, which further increase the emissions of green house gases into the atmosphere.

Additionally, high crude protein/nitrate-rich pastures cause a number of animal health issues. While rumen bacteria attempt to convert non-protein N into usable protein, the bacteria burn much energy doing so, and as a result the animal draws from its body reserves of carbohydrates and stored fats (ketosis), eventually losing body condition and becoming run down and stressed. High concentrations of nitrite produced by the reduction of nitrate-rich pasture to ammonia in the rumen also give rise to nitrite poisoning (toxicosis). Nitrite is absorbed into the blood stream and combines with haemoglobin to form methaemoglobin. As methaemoglobin is unable to carry and transport oxygen it causes death through anoxia. It also suppresses oxygen transfer to the foetus, causing oxygen starvation and the abortion of the foetus. Lack of sufficient oxygen due to nitrate/nitrite toxaemia is a common cause of infertility and high empty rates. High nitrate levels also suppress the production of Vitamin E, a key vitamin in protecting oxygen supply to the foetus.

PLATE 22 **Assessing the sugar content**

Assessing the sugar content (Brix) of pasture sap with a hand-held refractometer.

High crude protein/nitrate-rich pastures and the resulting high nitrate/nitrite/ammonia levels in the rumen and subsequently the blood, also raise the blood pH to levels above the 7.3 required for a healthy animal. The overly alkaline gut and elevated blood pH (alkalosis) causes a range of metabolic disorders, including increased susceptibility to pulmonary emphysema, mastitis, laminitis, scouring, severe dags, and, if the pH rises above 7.4, death. Moreover, high pH affects the tenderness, flavour, colour and shelf life of meat.

Pastures can contain cyanogenic glycocides (hydrocyanocides) in new and rapidly growing shoots, and particularly during the spring flush. Growth rates are exacerbated by the addition of soluble, salt-based nitrogenous fertilisers during this period, producing crude protein/nitrate-rich pasture and subsequent alkalosis. Hydrocyanocides break down to hydrocyanic acid (HCN or hydrogen cyanide) under overly alkaline conditions in the rumen, causing cyanide poisoning and death.

High nitrate levels also suppress the production of Vitamin D_3, an important component of the melanin pigment under the skin that protects the animal from the sun's ultra-violet rays. This makes the animal more susceptible to sunburn (spring eczema). In addition to creating nitrate/crude protein-rich pastures, the excessive use of N causes luxury uptake of K, which suppresses the absorption of Ca, Mg (and Na) in the animal, causing milk fever (hypocalcaemia) and grass tetany (hypomagnesaemia). While attempts to manage the effects of high K levels often include the use of magchloride ($MgCl_2$) and causmag (MgO), such products would not be necessary if the appropriate fertilisers were used and the uptake of Ca and Mg not suppressed. The use of some forms of chlorides (such as KCl) and caustics should be avoided where possible.

High levels of N in the soil and pasture can promote the pathogenesis of viruses, bacteria and fungal disease (see p. 54), and insect pests. The application of optimum levels of Ca can help counterbalance the effect of N, particularly when added in conjunction with Na, B, carbohydrates, humates, and organic acids.

One of the keys to successful pastoral farming is to grow pasture with a high sugar (energy) content (with Brix levels of 12 or more) and a high nutrient density. This is achieved by ensuring a good mix of pasture species, including a good herb and clover content, and by promoting the photosynthetic pathway through ensuring the presence of key sugar-making elements and the subsequent conversion of the sugars into fats, carbohydrates, starch and mature protein. In addition to N, <u>P</u>, <u>K</u>, and <u>S</u>, this requires <u>Ca</u>, Mg, <u>Na</u>, Fe, <u>Mn</u>, Cu, <u>Zn</u>, Mo, Co, <u>B</u>, Cl, B vitamins, vitamin C, adenosine triphosphate (ATP), and good soil life. An example of pastures developing a higher nutrient density and nutritional value after just one year in biologically grown pasture versus conventionally grown pasture is given in Table 5 and Figure 4. Correcting nutritional imbalances by raising the nutrient density and sugar level will also help to curtail or eliminate insect pests. Moreover, the presence of adequate levels of sugars, carbohydrates and starch in the pasture are vital because they are acidifiers, countering the alkaline effect of nitrates and other nutrients, and so help maintain the pH of the rumen at optimum levels. Soluble carbohydrate concentrations are influenced by sunlight and Brix (sugar) levels are therefore best measured mid-afternoon on sunny days (Plate 22). Overcast conditions will reduce soluble carbohydrate concentrations.

In addition to raising pasture sugars levels, rumen function (and feed-conversion efficiency) is improved by ensuring yttrium and cobalt levels are adequate in the pasture. To enable the bacteria in the rumen to produce the vitamin B_{12} necessary to promote efficient digestion, Co levels in the herbage should be of the order of 0.1–0.15 mg/kg. The animal is better able to store trace elements in its organs and glands and utilise them over a longer term if the nutrients are adsorbed through the digestive system, rather than being administered as generic forms in drenches, bullets or injections.

The age of the pasture since grazing (i.e. the length of the regrowth period) also has a significant bearing on the chemical composition and nutritive value of the pasture. Pasture quality in the spring, summer, and autumn is greatest 25–40 days after grazing. Before that, the fibre, dry matter, and mineral (ash) content is lower and pastures are rich in nitrate-N and crude protein through insufficient time for the soluble carbohydrates (sugars), organic acids and mature protein to build up. After a period of approximately 4–6 weeks, the quality of the pasture starts to decline with cell age, increased lignification and fibre content, and because nutrients begin to translocate down from the leaf to the root system. Rapidly growing pasture requires approximately 5–6 week to mature, while slow growing grass needs only 3–4 weeks.

White clover (*Trifolium repens* L.) is important for pastoral agriculture, not only because of its ability to fix nitrogen, but also because of its high nutritive and feed value (high protein and high mineral content), its seasonal complementarity with the growth pattern of grasses (perennial ryegrass), and its ability to improve animal feed intake and utilisation rates. While the quality of ryegrass is high in the spring, clover and herbs (such as chicory) are able to maintain their high nutritive value in the summer. White clover and herbs enhance the palatability of the pasture and because of their high digestibility and metabolisable energy, are utilised more efficiently than grasses, thus increasing the energy level, body condition, live-weight gain and reproductive function of the animal. The high digestibility of clover and herbs also gives rise to increased milk production with high protein, lactose and fat yield and a more efficient use of feed nitrogen, reducing the concentration of N in the blood and excreta. Furthermore, the more efficient digestion of clover and herbs enables the animal to better utilise the energy content of the pasture, converting it to meat, milk and fibre instead of methane and carbon dioxide. 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. In addition, the meat tends to have a higher Omega 3 content, a better flavour, and the animal has a higher kill-out weight due to a higher muscle:fat ratio.

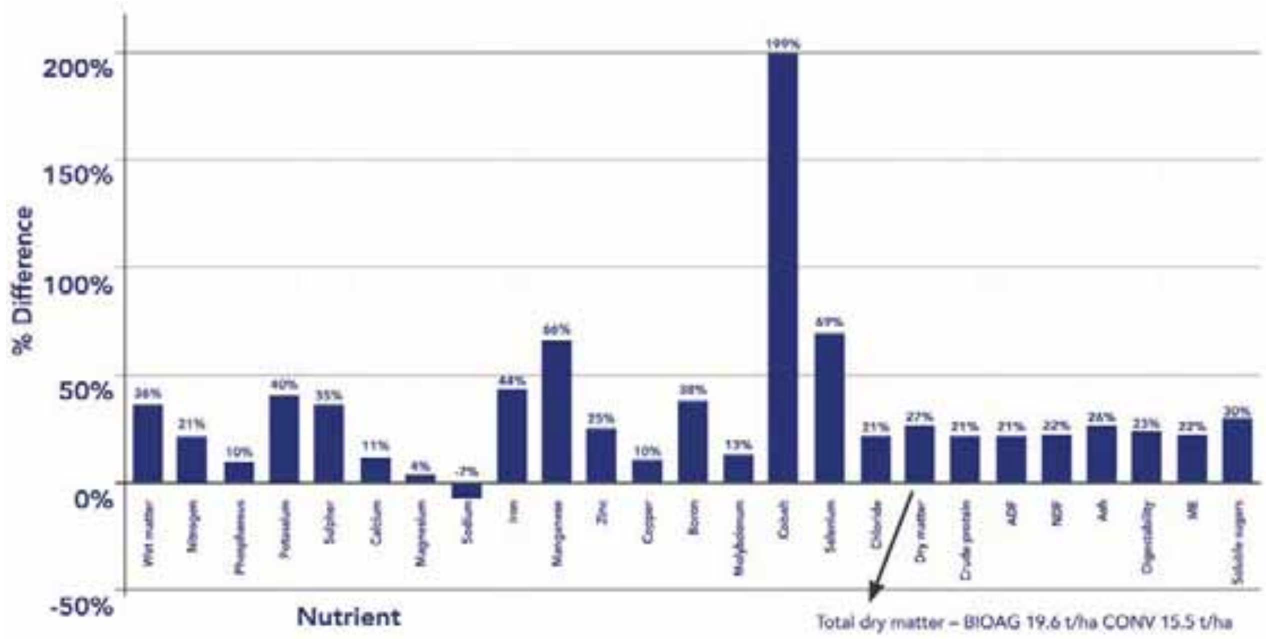
Clover drives the growth rates in lambs and, because of its high feed quality, stock generally gain more live-weight on white clover (growing 90 percent faster) than on perennial ryegrass. Diet selection studies show sheep prefer around 70 percent (dry matter) of their intake to come from white clover and 30 percent from grass. While cows milk better on clover pastures, the clover content of dairy pastures, often around 15–20 percent, is lower than the 50–70 percent needed for maximum milk solid production. A clover content in dairy pastures of at least 30–50 percent DM is also required for maximum pasture growth. Clearly, a greater proportion of white clover in mixed pastures would be beneficial to animal production. This can be achieved by promoting the condition of the soil, a higher level of N fixation through strong clover nodulation and the enhancement of free-living N-fixing bacteria, good grazing management practices, and meeting the nutritional requirements of clover including the appropriate use of specific forms of fertilisers other than nitrogen. The frequent and heavy use of fertiliser-N suppresses N-fixation, clover content, and clover growth, and limits clover recovery once N rates are reduced (see pp. 44–45). Because of this, 30 percent of clover DM in the pasture sward is not achievable and the pasture will therefore not meet the criteria required to be in good condition as defined in Plate 21.

TABLE 5 **Nutrient densities[1] of biologically grown pasture versus conventionally grown pasture**

Treatment	N	P	K	S	Ca	Mg	Na	Cl	Fe	Mn	Zn	Cu	B	Mo	Co	Se
	(%)								(mg/Kg)							
Biologically grown pasture	3.24	0.39	3.20	0.40	0.62	0.23	0.17	1.04	159	89	178	6.8	5.8	1.43	0.19	0.19
ConventionallY grown pasture	3.40	0.42	2.98	0.32	0.59	0.25	0.22	0.93	120	59	150	6.8	5.4	1.66	0.07	0.07

[1] Mean of 5 cuts taken in the autumn and spring. Data from the first year of field trials on a Waikato dairy farm; courtesy of Abron Living Soil Solutions .

FIGURE 4 **Nutrient level improvements in pasture**



Nutrient level improvements of biologically grown pasture versus conventionally grown pasture on a Waikato dairy farm. Values represent the mean of nine analyses of samples taken over an 11 month period and adjusted for differences in total dry matter production; courtesy of Abron Living Solutions.

Assessment

1. The N-fixing ability of a pasture can be assessed by the density, size, colour and depth of clover nodules.
2. Remove three to four clover plants with a spade, pushing the spade down to a depth of 250 mm. Gently shake the soil free exposing the root system and clover nodules (Plate 23).
3. Assess the number of nodules, their size, the depth at which they occur, and the colour of the leghaemoglobin within the nodule (Plate 24), and colour, compare with the criteria given in Table 6. Clover nodules are best assessed in the spring when leaf growth and N demand is greatest, but can be checked at any time of the year provided the plant isn't under stress through defoliation, drought, or soil and air temperatures being too high or low.
4. Nodules on clover have a short life-cycle of 3–4 weeks. Healthy nodules start as white, then become pink on the surface as red leghaemoglobin develops inside the nodule, at which point it become active, fixing N_2. The redder the colour, the more active it is. The nodules then decline as the leghaemoglobin decays to a yellow bile pigment (Plate 24) and eventually becomes elongated and white or grey again, appearing like a deflated balloon. Depending on their stage of maturity, nodules will also display a range of sizes varying from very small up to 3–5 mm. Nodules on mature healthy roots will therefore have a range of colours, shapes and sizes. To assess the degree of redness of the leghaemoglobin, select 3 or 4 of the pinkest nodules and split them in half between your fingernails and observe the colour with a magnifying hand lens. Discard any nodules showing yellow bile pigment because they are becoming inactive and nearing the end of their cycle.

Importance

CLOVER NODULES are produced in response to invasion through the root hairs by *Rhizobium*, a bacterium which infects and stimulates the proliferation of root cells to form nodules. Once the nodule is formed, the bacterium multiplies and changes form into a bacteroid that contains a nitrogenase enzyme capable of reducing atmospheric nitrogen gas to ammonia ($N_2 + 8H^+ \rightarrow 2NH_3 + H_2$). The nitrogenase enzymes break the triple bond holding the two N atoms of the N2 molecule, and adds hydrogen to form ammonia. The reaction requires hydrogen and a considerable amount of energy in the form of adenosine triphosphate (ATP) and carbohydrates from photosynthesis. The enzyme has two components, a molybdenum-iron protein and an iron protein. Molybdenum and iron must therefore be present in adequate amounts to enable the production of the nitrogenase enzyme and therefore the fixation of N_2. While *Rhizobium* is an aerobe, nitrogenase enzymes cannot function in the presence of oxygen and so oxygen levels are kept low by a diffusion barrier on the outer wall of the nodule, by high bacterial respiration rates within the nodule, and by the presence of leghaemoglobin. The critical function of leghaemoglobin is to absorb O_2 and transport it within the anaerobic zone to the bacterial cells to support their respiration. Leghaemoglobin can only be produced if levels of Fe, Mn, Zn, Co, Se and in particular Cu (the blood elements) are adequate. A pink/red colour

PLATE 23 **Clover nodules**

Clover roots showing strings and clusters of distinct healthy pale pink nodules. Photo taken in the spring: Courtesy of John Brock.

PLATE 24 **Inside a clover nodule**

Clover nodule split open showing brownish red leghaemoglobin (LHb). Note the decay of the LHb to the yellow bile pigment above the red area. Photo: Courtesy of Michael Templer.

inside the nodule indicates the nodule is actively fixing N; the redder the colour, the more active it is. The ability of the *Rhizobium* bacteria to fix N also depends on whether the strains of rhizobia present in the soil have an effective nitrogenase system, and if not, then clover seed needs to be inoculated with effective strains.

The ammonia produced by N-fixation is rapidly converted to ammonium (NH_4^+) and taken up by the plant to produce protein and organic N compounds. The N fixed by clover nodules is only released to other pasture plants such as grasses by a combination of two processes. First, when the clover plant dies and decomposes, the organically bound N compounds are mineralised by a wide range of bacteria and fungi in the soil to release N in the form of plant available ammonium (NH_4^+). Under aerobic conditions, the majority of ammonium is converted to nitrate (NO_3^-), another plant available form of N by nitrosomonas and nitrobacter bacteria (a process known as nitrification). Second, most of the N ingested by grazing animals is returned to the soil as urine, which then hydrolyses to urea. Urea is converted to ammonia by the urease enzyme followed by its hydrolisation to ammonium and then nitrification to nitrate-N. A possible third but minor mechanism could involve the direct excretion of small amounts of N through root leakage from intact growing legumes.

Depending on its relative dominance in a sward, white clover is able to fix up to 300 kg N/ha/year in high-producing sheep farms, and up to 380 kg N/ha/year in dairy farms. Higher levels of N fixation could possibly be achieved if optimal conditions for N fixation were provided. The actual amount of N fixed is very dependent on a number of factors including the performance and condition of the clover nodules. Factors that limit white clover growth often result in much lower N fixation rates of 80–150 kg N/ha/year. Such factors include moisture stress, high temperatures, cultivar choice, competition from grasses and incompatible companion species, pasture establishment, shading, grazing management, endophytic toxins from ryegrass, pest and diseases, soil acidity (pH <5.8), low soil carbon, low soil fertility (other than N) including low Ca levels, and poor soil aeration. Poorly aerated and compacted soils have less air and consequently less N available for biological fixation. In addition to the elemental requirements for the production of nitrogenase and leghaemoglobin, white clover plants require adequate levels of N, P, K, S, Ca, and B for root development and growth. Aerobic N-fixing micro-organisms also require adequate levels of Ca and Co, and good soil aeration to function at optimum levels.

N-fixation by clover nodules is further governed by the amount of mineral-N in the soil. Clover prefers to take up mineral-N than fix N from the atmosphere because it is a more energy-efficient process and therefore has less energy cost to the plant. Clover will only resort to N-fixation when a deficiency in N occurs within the plant. Thus the frequent and heavy use of water-soluble N in the form of urea, anhydrous ammonia or nitrate will suppress N-fixation, clover content, and clover growth, and limit clover recovery once N rates are reduced.

TABLE 6 **Visual scoring (VS) clover nodules**

Visual score (VS)	Clover nodules
2 [Good]	Clover roots have strings and clusters of lots of nodules (4–8 per 20 mm) and occur to a depth of 150–200 mm; many are large (2 mm). At least 50 percent of the nodules have a distinct pale pink hue on the surface and a bright red or brownish red leghaemoglobin content that bleeds when split open and squeezed.
1 [Moderate]	Clover roots have a moderate number of nodules (1 per 20 mm) to a depth of 75–150 mm. The largest nodules are of medium size 1–2 mm) and have a faint pale pink hue on the surface and a pink to pale reddish brown leghaemoglobin content when split open.
0 [Poor]	Clover roots have few or no nodules and only occur in the upper 75 mm of the soil. Nodules are small (< 1 mm) and are white on the surface with little or no signs of leghaemoglobin when split open

Nitrogen can also be fixed by free-living N-fixing aerobic *Azotobacter* bacteria and by anaerobic *Clostridium* bacteria. The fixed-N (up to 10–15 kg N/ha/yr) is made available to the plant when the bacteria die and decompose. *Azotobacter* bacteria need good aeration, high levels of available C, and non-acidic soils to function in large numbers. Under favourable, non-acidic, well-aerated soil conditions with optimum levels of trace and major elements including Ca and C, as well as a good earthworm population, free-living N-fixing bacteria could potentially produce substantially more than 10–15 kg N/ha/yr.

Nitrogen fixing bacteria, be they free-living in the rhizosphere, confined to nodules on plant roots, or existing as endophytes in leaves or stems, derive most of their energy from dissolved organic carbon (liquid sugar) fixed during photosynthesis. N-fixation is therefore very dependent on the flow of liquid carbon from the leaf to the roots.

The rate of N-fixation depends on the demand for N, which is governed by the clover growth rate. Because N-fixation is influenced by the amount of mineral-N in the soil, clover growth is not necessarily a direct indicator of N-fixation. In spring, grasses are more active and use most of the soil N, and while clover growth may not be high, N-fixation will be. In summer when clover is more active, grasses are less active and soil N can accumulate and clover N-fixation may be lower.

Assessment

❶ Assess the number of weeds (using the percentage chart on p. 48) and variety of undesirable weeds in the pasture, and at what level their presence detracts from the value of the pasture. Undesirable weeds include ragwort, barley grass, bristle grass, water pepper, willow weed, wild carrot, mayweed, hedge mustard, buttercup, duckweed, and thistles.

In making your assessment, consider how often a given level of weed infestation occurs in the paddock from season to season, and at what level it is perceived to be a problem. Consider also your grazing management and the need for weed control measures, including the use of herbicides, biological control agents, mowing, steaming, cultivation, pastoral renewal, and other measures taken to deal to weeds before they go to seed. Make your assessment according to the photos and criteria given in Plate 25 on the basis of what the field would look like without any weed control measures except for grazing management.

Importance

WHILE SOME WEEDS are beneficial and contain a number of essential nutrients for stock, others have little nutritional value, are difficult to digest, can be poisonous, and generally reduce the overall value of the feed. Weeds compete with desired pasture species for water, nutrients and growing space, displacing more beneficial, high-producing pasture species, thereby encouraging the use of clover-damaging herbicides. They allow poor pasture quality to develop, reducing pasture utilisation and plant and animal production.

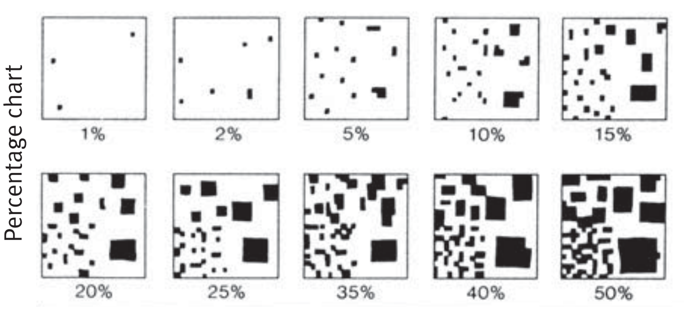
While weeds can occur for a number of reasons, they can be useful indicators of the condition of the soil, including the level of compaction, soil aeration and waterlogging, nutrient fertility, pH, the amount and type of organic matter, and the microbial biomass. It is commonly believed that healthy soils support weeds and desirable pasture species equally well. In the same way that insect infestation indicates unhealthy plants with a nutritional imbalance, a weed infestation indicates something is not right with the soil, which is suppressing the growth of high producing pasture species and providing an environment favouring weeds. Soil structural degradation resulting from stock treading (pugging), wheel traffic, over-cultivation, or soil dispersion due to a low Ca:Mg ratio or high Na levels, reduces soil aeration, soil drainage, available water-holding capacity, nutrient uptake, and the rooting potential of the crop, allowing weeds to establish and compete with the crop. Lighter soils with a coarser textural class can have more weeds than heavier soils with a finer textural class, while acidic soils can have a greater variety of weeds than non-acid soils.

PLATE 25 **Visual scoring (VS) of weeds**

GOOD CONDITION VS = 2
Pasture has few or no weeds.

MODERATE CONDITION VS = 1
Weeds are very common covering 5–10 percent of the ground surface.

POOR CONDITION VS = 0
Weeds are abundant covering ≥ 20 percent of the ground surface. They indicate either significant compaction, poor aeration, waterlogging, low functional organic carbon and Ca, or poor mineral and microbial composition.



Weeds will also develop and thrive in soils that have a poor mineral and microbial balance. Weeds will grow and proliferate where there is a Ca and P deficiency and an excess of K and Zn. They will develop where there is an imbalance of Fe to Mn, a lack of biologically available Ca, a lack of biologically active carbon including humus and humic acids, and where there are high nitrate levels, and a lack of bacteria or fungi. Pastoral soils need to maintain a fungal to bacteria ratio of 0.75:1 (or 1:1), which is necessary to preserve and promote pastoral plants. An imbalance of this ratio along with poor soil nutrition could explain why pastures may show poor persistence and a tendency to revert to other plant species such as woody weeds.

Thistles, including the nodding, wing, Scotch and Californian thistles, are some of the most annoying and destructive weeds: the smothering and competitive effects of rosettes reduce pasture production, and the prickly leaves discourage even grazing and good pasture utilisation. Thistles can indicate the soil is deficient in Ca and bacteria and high in K and S. An infestation of thistles would suggest soil conditions and fertility are insufficiently adequate to maintain a complete, vigorous pasture cover and the high growth rates required to reduce seed germination and kill young seedlings and developing rosettes.

Broad-leaved weeds such as dock can develop on soils that are moderately acidic with moderately high fungal levels. They like a soil environment that is low in Ca and P and high in N and K, where available K greatly exceeds the available P. High nitrate levels also help to promote seed germination. Dock can further indicate a decline in the C:N ratio. If the available K continues to increase relative to P, a point may be reached where herbicides cannot control the broadleaf weed. While they are poor competitors and germination is inhibited under a dense leaf canopy, dock can establish and take hold in open or disturbed patches of pasture due to overgrazing, compaction, pugging, and the uneven application of slurry or manure. Some would argue that docks in grassland are not weeds because they contribute trace elements and herbage to a grazing animal's diet and hence do not need to be controlled. Broad-leaved dock is relatively high in P and K in the leaves, and is particularly high in Mg. Cattle fed on herbage containing docks help to prevent bloat because tannins in the dock leaves help to protect plant proteins from digestion and degradation and precipitate out soluble proteins in the rumen, thus preventing the formation of a degraded protein-based foam.

Barley grass is found on rough bare ground in summer-dry, seasonally stressed areas, on soils deficient in Na, and on the margins of cultivated fields. Barley grass does not compete well against a vigorous perennial ryegrass/white clover sward on fertile, moist soils. **Ragwort** is not common in seasonally stressed, summer-dry pastures and is more usually associated with wetter areas, and on soils low in Ca, P, Co and bacteria, and high in K (particularly when using muriate of potash). The ragwort seed is well adapted to areas of local disturbance, as may be found in well-trafficked, compacted areas. Ragwort does not compete well against strong competition from vigorous, rapidly growing perennial ryegrass/white clover pastures on good quality, highly fertile soils. Ragwort is toxic to stock and can induce photosensitization, jaundice, weight loss, and impairment of liver function. **Dandelions** indicate a Ca, P, vitamin A and in some cases an Fe deficiency in the soil. Their occurrence is exacerbated by Mg, Zn and the excessive use of K (muriate of potash), which further suppresses Ca levels. **Buttercup** grows especially well on wet, poorly drained, poorly aerated soil, and soils that are low in Ca, P, humus and bacteria and high in K (particularly if using muriate of potash). It is tolerant of compaction and grazing, and fresh plants can be bitter and toxic to grazing animals.

The condition and properties of the soil have a major bearing on whether the pasture is able to grow in a sufficiently vigorous way to out-compete, and prevent or restrict the establishment and growth of weeds. Competitive suppression by vigorous pasture growth plays a major role in preventing weed establishment. Weed suppression can also occur after a pasture is sown by the production of auxins (or plant growth hormones) when the seed germinates. Auxins limit or stop the germination of other seeds from either pasture or weeds. While this suppression lasts for only 1–2 days in poor quality soils, it can last for 6–8 weeks in biologically active, well-aerated soils, thus providing an effective, natural weed control. The application of liquid calcium incorporating a form of organic carbon such as molasses or humic/fulvic acids (to act as a food supply for soil microbes), along with the addition of an organic form of phosphorus and selected trace elements such as B, Co and Se, can help alter the soil environment in such a way that weeds are suppressed. As the soil chemistry adjusts and nitrogen is converted to an organic form (freely available to mycorrhizal fungi but not to annual weeds), the incidence of weeds, pests and diseases that are stimulated by low levels of microbial diversity and high rates of non bio-friendly, water soluble potassic and nitrogenous fertilizers, will decline.

Changing the soil environment can successfully deal with any weed problem and can provide a more effective solution than the application of straight herbicides, which gives a short-term and often limited response. However, where weeds are an initial problem, the incorporation of herbicides into a solution containing ammonium humate or fulvic/humic acids with a pH modifier, can provide good weed control. Such a mixture enables the amount of herbicide used to be reduced by 25–35 percent, and also helps buffer the effect of the herbicide on soil life. The regular use of herbicides and pesticides have an adverse effect on soil microbes (including mycorrhizal fungi), which are responsible for maintaining the nutrient balance and availability of nutrients in the soil. The quick-kill approach using chemical herbicides only addresses the symptoms and does nothing to rectify the underlying cause.

Assessment

❶ Assess pasture growth since the last grazing by pasture probe, rising plate, herbage cut measurements, or alternatively by visual estimation (Plate 26), and compare with the criteria given in Table 7. If this information is not available, use visual approximations of dry matter (DM) production levels. For a reliable comparison, make assessments at the same time of year, preferably in mid spring. Consider also the total dry matter production per annum.

Importance

HIGH PASTURE PRODUCTION AND GROWTH RATES depend on good soil structure and aeration, good soil fertility, earthworm and microbial activity, available water, seasonal weather conditions, and the maintenance of good residual levels (≥ 1 800 kg DM/ha) after grazing. Just as pasture quality has a marked effect on live-weight gain, milk and fibre production, livestock health, and reproductive performance, so does pasture quantity. Intake is influenced in part by the amount of pasture offered to the animal. The more offered, the more can potentially be eaten, up to a maximum where increased DM production has no more influence on intake and live-weight gain. For stock to be in good condition at calving and lambing, an adequate pasture cover of 2 000 kg DM/ha is needed, and pastures need to be capable of rapid regrowth.

Treading damage on compacted moist soils can reduce pasture production by up to 27 percent; on pugged (deformed) wet soils, however, the reduction can be as much as 45 percent. As a consequence, farmers are forced to budget for extra feed (up to 30 percent more) in the winter. Moderately pugged ground with a moderate VSA soil structure score (of 1) can give rise to a loss of 200 kg DM/ha/month or 13 kg milk solids/ha/month. Assuming a payout of $5.50/kg MS, this would equate to a loss of approximately $715/ha/yr or $107,250 in income from a 150-ha dairy farm.

TABLE 7 **Visual scoring (VS) pasture growth**

Visual score (VS)	Pasture growth	Dry matter production (tonnes/ha/yr)	
		Lowland farms	Upland farms (300 m [1 000 ft] above sea level)
2 [Good]	Good pasture growth	17	13
1 [Moderate]	Moderate pasture growth	13–15	9–11
0 [Poor]	Poor pasture growth	< 11	< 7

PLATE 26 **Assessing dry matter production**

Assessing dry matter production and pasture growth rates with a rising plate meter.

Treading damage and the loss of dry matter production can be reduced significantly by grazing paddocks when the soil is sufficiently dry to minimise compaction and pugging. To assess whether soil conditions are suitable for grazing, apply the 'worm test' (Plate 47, p. 70). Take a piece of soil (half the volume of your index finger) and press firmly with your fingers to form a pencil. For silty soils, if you can roll a worm 10 mm wide by 50 mm long (7 mm wide by 50 mm long for clayey soils) between the palms of your hand without it cracking, the soil is too wet to graze. If the worm cracks when it is 10 mm wide for silty soils (7 mm for clayey soils), the soil is ready to graze. Compacted, pugged pastures and the subsequent reduction in dry matter production can also be ameliorated by artificial soil aeration. To assess whether soil conditions are suitable for aerating, apply the 'worm test' (Plate 47, p. 70). Aerating the soil can increase DM production by 33 percent after 6 months and by 52 percent after 8 months. Pasture composition and nutritional value are also significantly improved.

pasture colour and growth relative to urine patches

Assessment

❶ Compare the colour and growth of the pasture between urine patches with the colour and growth of the urine patches, and compare with the three photographs and criteria given in Plate 27. The best time to carry out the assessment is just before the next grazing in the autumn, late winter and late spring, avoiding very cold and wet weather. In making the assessment, consideration must be given to the time of year, the pasture species, stage of growth, soil moisture and temperature conditions, and also the presence of pests and diseases (e.g., nematodes). If the pasture receives more than 30 kg/ha/yr of artificially applied nitrogen, consider what the pasture looks like just before the application of N.

Importance

THE COLOUR AND GROWTH OF THE PASTURE RELATIVE TO THE URINE PATCHES and blemishes on the leaf can provide a good indication of the nutrient status and condition of the soil. Pasture colour depends on a number of factors, including a deficiency or excess of N, P, S, Ca, Mg, Fe, Mn, Cu, B, Co, and Mo. Chlorosis (or yellowing of pasture) due to the loss or inadequate formation of chlorophyll, commonly occurs as a result of low N, S, Mg, Fe, Mn, Cu and Zn levels in the soil, low soil and air temperatures, prolonged cloudy days, and poor soil aeration resulting from compaction and waterlogging.

The difference in pasture growth in and between urine patches can distinguish between pastures that are and are not reliant on fertiliser-N to generate growth. The frequent and excessive application of N (especially during dry conditions) together with certain types of fertilisers, herbicides and pesticides can adversely affect the biological regime and nitrogen cycle of the soil, and can also suppress other elements critical for plant growth. As a result, pastures can become dependent on a 'fix' of nitrogen or fertiliser to stimulate growth. Yellow, stunted grass between darker green urine patches (pastoral chickenpox), can be a further sign that the nitrogen cycle has broken down and the utilisation and supply of N and other nutrients by micro-organisms has been adversely affected. In other words, the engine room of the soil, as discussed on p. 21, has become 'rusty' and no longer has the 'horse power' to produce the dry matter required. The addition of N in such cases will only give a short-term pasture response, and an ongoing dependency on N can result – no applied nitrogen, no grass.

Yellow, stunted grass between urine patches can also occur as a result of a N and S deficiency caused by a reduction of plant-available forms of N and S to plant-unavailable forms in poorly aerated, waterlogged soils (pp. 6, 13 & 28). S and N can only be utilised by plants in the oxygenated sulphate (SO_4^{2-}), nitrate (NO_3^-) and ammonium (NH_4^+) form. Plants can also only utilise N if S is present in oxygenated sulphate form.

PLATE 27 **Visual scoring (VS) pasture colour and growth relative to urine patches**

GOOD CONDITION VS = 2
Pasture colour is uniformly deep green with little difference in growth between urine patches. The odd colour blemish on leaves may be apparent within a broad area.

MODERATE CONDITION VS = 1
Moderate difference in pasture colour and growth between urine patches. Pasture is yellowish green or medium green between urine patches. Few colour blemishes on leaves may occur.

POOR CONDITION VS = 0
Significant difference in pasture colour and growth between urine patches. Pasture is quite yellow between urine patches. Colour blemishes on leaves may commonly occur.

In addition to a yellowing of the pasture, discolorations or blemishes on the leaf can indicate mineral deficiencies (Plates 28–35). Nutrient deficiencies or excesses can suppress the availability of other nutrients. For example, high P levels can suppress the uptake of S, Zn and Cu while high S levels can suppress the uptake of P and Mg. Excess N can strip Ca from the soil, block Mn, Zn, B and Cu uptake, and cause the plant to luxury feed on K, which in turn can also tie up Mn and B, and suppress the utilisation of Ca and Mg by the animal.

Moreover, N-rich pastures growing on urine patches are often avoided by cattle; they will only eat it when the feed supply is short, or when its sugar level rises. When nitrates exceed 0.23 percent of the DM, nitrate poisoning (toxicosis) is likely to occur as nitrate is reduced to nitrite (NO_2^-) in the rumen. N-rich growth patches also bring increased risk of mycotoxins and toxic substances produced by fungi, which results in milk production losses, reduced feed intake, feed refusal, unthriftiness, rough hair-coat, ketosis, retained placenta, metritis, fatty livers, reproductive problems and poor body condition.

PLATE 28 **Phosphorus deficiency in clover**

Photo: T. Wallace (1961)

Phosphorus deficiency in clover: Dull bluish green or yellowish green leaves with small bronze spots over the surface.

PLATE 29 **Phosphorus deficiency in grass**

Phosphorus deficiency in grass: Leaves show a distinct purple colouring.

PLATE 30 **Magnesium deficiency in clover**

Photo: T. Wallace (1961)

Magnesium deficiency: Interveinal chlorosis and of the leaf margins

PLATE 31 **Calcium deficiency in clover**

Photo: H.B. Sprague (1964)

Calcium deficiency: Leafstalks collapse and wilt; leaves are chlorotic with scorched margins.

PLATE 32 **Potassium deficiency in clover**

Potassium deficiency: White spots on margins of leaves.

PLATE 33 **Sulphur deficiency in clover**

Sulphur deficiency: Pink clover leaves.

PLATE 34 **Boron deficiency in clover**

Photo: T. Wallace (1961)

Boron deficiency: Reddish margins of clover leaves; thickened & stiff stems.

PLATE 35 **Copper deficiency in grass**

Photo: W. Bergmann (1993)

Copper deficiency: Chlorosis of the margins and tips of grasses.

Assessment

❶ Assess pasture utilisation by estimating the proportion of pasture that has been well grazed or poorly grazed, and the proportion not smeared or trampled into the mud by grazing animals, and compare with Plates 36–38 and the criteria in Table 8. In making the assessment, consider the time of year, the pasture species, stage of growth, soil moisture and temperature conditions, radiation levels from the sun, grazing management practices, stocking rate, and the type and amount of fertilisers applied.

Assessments should be made at or as near the end of the grazing period.

Importance

PASTURE UTILISATION provides a good indication of the quality and palatability of the pasture and can be a useful guide to the nutrient status and condition of the soil. Pastures have a high palatability if they are rich in sugars and carbohydrates relative to protein, with a high nutritional value, containing many of the essential elements required and sought after by the animal. As a result, stock graze the whole field with a utilisation of around 80 percent. Conversely, pastures that are protein rich and deficient in sugars and essential elements have poor palatability. Stock graze selectively and roam a lot, and pasture utilisation can be reduced to 40 percent. The nutritional value of the pasture and the degree of utilisation also depend on soil aeration and the vigour and distribution of the root system. Pastures with an extensive root system in well-aerated soils are able to utilise a greater reservoir of water and nutrients. Poorly aerated soils have limited root systems and suppress the availability of elements in a form required by the plant (see pp. 8, 13 & 28). Palatability can further be affected by the pasture being contaminated with fungal toxins.

Utilisation of pasture can also be influenced by treading damage (pugging) when wet. As a result, pastures can experience prolonged surface ponding and are easily trampled into the mud. This makes the pasture both inaccessible and unpalatable to stock. Trampling and surface ponding can reduce pasture utilisation by 20–40 percent.

TABLE 8 **Visual scoring (VS) of pasture utilisation**

Visual score (VS)	Pasture utilisation
2 [Good]	Good pasture utilisation with high palatability and only a little of the pasture being trampled into the mud.
1 [Moderate]	Moderate utilisation of pasture due to moderate palatability or a significant amount of pasture being covered by, and trampled into the mud.
0 [Poor]	Poor utilization of pasture due to poor palatability or a large proportion of pasture being covered by, and trampled into the mud.

PLATE 36 **Good utilisation of pasture**

Even grazing and good utilisation of pasture due to high palatability.

PLATE 37 **Poor utilisation of pasture with low palatability**

Poor utilisation of pasture with low palatability. Stock selectively graze and roam a lot.

PLATE 38 **Poor utilisation of pasture**

Poor utilisation due to severe trampling into the mud.

Assessment

1. Remove a piece of soil 200 mm square by approximately 300 mm deep with a spade from the side of the hole where the 200-mm cube was removed for the drop shatter test. With the help of a knife, carefully loosen the soil between the roots and then expose the root system by gently shaking the soil free by tapping the soil sample against the edge of the hole. Compare both the length and the density of the roots with the three photographs and criteria given in Plate 39.

The root length and root density is best assessed in late autumn–early winter when maximum root development occurs, but can also be assessed in late winter–mid-spring when soil moisture and soil temperatures are usually not limiting pasture growth.

Importance

ROOT LENGTH AND ROOT DENSITY provide good indications of the condition of the plant root system. Pastures with deep roots and a high root density are able to explore and utilise a greater proportion of the soil for water and nutrients compared with pastures with a shallow, thin root system. Dry matter production and tillering is therefore likely to be greater, root pulling less of a possibility, and pastures will have a lower susceptibility to drought stress and recover quicker when the rains come. Pastures with a dense, deep, vigorous root system also raise soil organic matter levels and soil life at depth, thereby sequestering (adding) significant amounts of carbon. The physical action of the roots and soil fauna, and the glues they produce, promote the development of soil structure, soil aeration and drainage. Worm-populated soils also have many tunnels that are coated with mucus and rich in nitrates. Plant roots take advantage of the tunnels as easy-growth channels, extending quickly by taking nutrition from the nitrogen-rich mucus and water as they go. The presence of clover root nodules at depth supplying nitrogen as a result of N fixation further encourages the development of the root system.

A deep, dense root system provides huge scope for raising production while at the same time having significant environmental benefits. Pastures are less reliant on frequent and high application rates of fertiliser and nitrogen to generate growth, and available nutrients are more likely to be sapped up, reducing losses by leaching into the groundwater and waterways.

Root length, root density, plant growth and vigour can be restricted by the mechanical impedance of roots and the lack of soil pores due to soil compaction, a hardpan or rock. Restrictions can also occur due to low soil moisture, soil temperature and pH, aluminium toxicity, salinity, sodicity, major and trace element deficiencies, the application of excess nitrogen causing lazy plants, low mycorrhizal fungi levels, soil-borne pathogens, a high or fluctuating water table and poor soil aeration. Anaerobic (anoxic) conditions due to prolonged water-logging and deoxygenation restrict root length and density as a result of the accumulation of toxic levels of sulphides, methane, alcohol (ethanol and ethylene), acetaldehyde and formaldehyde, all by-products of chemical and biochemical reduction reactions (see pp. 13 & 28).

PLATE 39 **Visual scoring (VS) of root length and root density**

GOOD CONDITION VS = 2
Good root length & root density with an evenly distributed root system.

MODERATE CONDITION VS = 1
Moderate root length & density with the root system being somewhat patchy.

POOR CONDITION VS = 0
Poor root length & density with the root system being restricted to limited areas.

Assessment

1. Assess the area of bare ground in winter or early spring. Compare the surface of the ground with the three photographs and criteria given in Plate 40. If there is canopy closure due to good growth, part the pasture with your hands and score at ground level. An assessment of an area of bare ground after a long dry period will show how much pasture has died from lack of moisture.

Importance

IN ADDITION TO STOCK CAMPING, DISEASE, INSECT PESTS AND DROUGHT EFFECTS, BARE GROUND is formed by the physical churning up of the soil from treading and pugging. This churning causes leaf and stem crushing, reduced tiller density, the uprooting or burial of plants, and root damage, all of which reduce tiller numbers and pasture density, vigour and growth. Weeds and less desirable pasture species can invade the resulting gaps, further reducing pasture production. Like surface relief, the area of bare ground can be a good indicator of below-ground damage.

Bare ground on fields with a slope can increase their susceptibility to water erosion. Good pasture cover on the other hand, and its below-ground root system, returns organic matter to the soil and promotes soil life including earthworm numbers and activity. The physical action of the roots and soil fauna, and the glues they produce promote the development of soil structure, soil aeration and drainage. As a result, infiltration rates and the movement of water through the soil increases, decreasing runoff, soil erosion, and the risk of flash flooding. Pasture cover on sloping ground also reduces soil erosion by intercepting high impact raindrops, and minimising rain-splash and saltation. Moreover, it acts as a sponge, retaining rainwater longer so that it infiltrates into the soil. The root system of good pasture cover further reduces soil erosion by stabilising the soil surface, holding the soil in place during heavy rainfall events. As a result, water quality downstream is improved, with lower sediment loading and lower nutrient and coliform content. The ground surface needs to have at least 70 percent cover to give good protection; ≤30 percent cover provides poor protection.

Good ground cover (with a high leaf-area index) intercepts and absorbs a large amount of carbon dioxide (CO_2) as it escapes from the soil. This increases pasture production as a result of the greater photosynthetic uptake of CO_2 and decreases the amount of CO_2 emitted into the atmosphere, decreasing the level of green house gas emissions.

PLATE 40 **Visual scoring (VS) of area of bare ground**

75% cover

GOOD CONDITION VS = 2
Pasture covers all or most of the surface area. Surface cover is ≥80 percent.

50% cover

MODERATE CONDITION VS = 1
Pasture shows significant areas of bare ground and sporadic growth with the ingression of weeds and white clover caused by treading damage. Surface cover is 40 percent and <60 percent.

20% cover

POOR CONDITION VS = 0
Large areas of bare ground (≤20 percent cover) occur because of treading damage and the reduction in density and vigour of the pasture. White clover and less desirable pasture species and weeds may have invaded degraded and bare areas

Surface cover photos: courtesy of A. Leys

Assessment

1. Assess, from visual evidence and local knowledge, the degree to which pastures are drought stressed during prolonged dry periods by comparing the greenness of the pasture with the three photographs and criteria in Plate 41. Assess also the level of dry matter production, whether drought tolerant species have become dominant in the pasture sward, and how quickly the pasture declines going into a drought and how quickly it recovers following the first rains, according to the criteria given in Plate 41.

Importance

THE DEGREE OF DROUGHT STRESS in dry periods depends on climatic conditions, grazing management, the drought tolerance of the pasture, and the condition of the soil, including the amount of water able to infiltrate into the soil and the water-holding capacity (AWC) of the soil. The latter is governed by soil depth, the length and density of the root system, soil texture, the number and size of soil pores, and amount of soil carbon. One part of soil humus (a relatively stable form of soil carbon) can retain a minimum of four parts of soil water. Pastoral soils with a good structure and soil life, including earthworm populations, have a large number of macropores and coarse and medium-sized micropores, and, subsequently, have a higher water-holding capacity than degraded soils with few pores. Soils with good structure also have high infiltration rates with little or no run-off and are able to capture most of the rainfall. Loamy and silty soils, and in particular soils with silt loam textures and good organic matter levels (of 15–30 percent), are able to store and retain a lot more plant-available water than very fine (clayey) and coarse (sandy) textured soils, particularly if the soil organic matter content is low.

Calcium (in a form such as lime) promotes the biological life, structure and porosity of the soil and therefore the AWC. Lime also converts to water by the following reaction, which increases the soil's resistance to drought: $CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$. Optimum levels of Zn and K promote the uptake of water and therefore water-use efficiency by facilitating the movement of water into plant cells. High K levels will suppress the wetting of soils and reduce Ca levels. Although Mg has an affinity for water, increasing plant-available water, too much Mg (and Na) disperses soil clay particles, causing the collapse of the soil structure and pores and consequently the reduction of their water-holding capacity. Ensure the soil has good amounts of Ca relative to Mg, with a Ca/Mg ratio of 7:1 for clayey soils, 5:1 for silty soils and 3:1 for sandy soils.

Mycorrhizal fungi can supply moisture to plants by exploring micropores not accessible to plant roots. They can also improve water flow by their hyphae bridging macropores. This wicking effect along the hyphae can be very significant in dry soils. Mycorrhizal fungi can also increase drought resistance by stimulating an increase in the number and depth of plant roots.

Pastures on good quality soils are slow to decline going into a drought and quick to recover following the first rains. Conversely, pastures on poor quality soils are quick to decline going into a drought and slow to recover following the first rains. This is particularly so for white clover.

PLATE 41 **Visual scoring (VS) of drought stress of pastures during prolonged dry periods**

GOOD CONDITION VS = 2
Pastures are slow to decline going into a drought and remain relatively green, with dry matter production able to hold on, albeit at low levels, further into dry summers. Recover is quick following the first rains. Pasture composition is dominated by ryegrass and white clover during dry periods.

MODERATE CONDITION VS = 1
Non-drought tolerant pastures 'brown off' significantly during dry summer months, although thin green patches are still present close to the ground. Dry matter production is very low and pastures become dominated during drought by the more drought- resistant cocksfoot, tall fescue, phalaris, birdsfoot, Lotus trefoil, meadow rice-grass, rats tail and small annual clovers. Deep rooted flat weeds and hawkbit may also be common. Pastures are moderately quick to decline going into a drought and recovery is somewhat delayed following the first rains.

POOR CONDITION VS = 0
With the possible exception of drought tolerant grass species and deep rooting herbs such as chicory, pastures brown off completely and pasture growth stops during dry periods. Pastures are quick to decline going into a drought and die off during times of prolonged drought. With the exception of subterranean clover and drought-tolerant species such as phalaris, pastures are slow to recover following the first rains.

Assessment

1. Assess the stock-carrying capacity of the paddock in relation to production costs and whether overall production costs have increased in order to maintain stock-carrying capacity.

In making your assessment, consider all production costs including, for example, the use of nitrogen, lime, additional fertilisers, feed supplements, soil aeration of the topsoil (Plates 42–45), subsoiling (deep ripping), artificial drainage, resowing, under-sowing, over-sowing, weed control, drenching, animal health issues, and veterinary costs, etc. Compare with the criteria given in Table 9.

Importance

PRODUCTION COSTS TO MAINTAIN STOCK-CARRYING CAPACITY can provide a good indication of the performance of the soil and pasture. While fertiliser should be seen as an investment rather than a cost, it is one of the major costs associated with farming. The amount, type and therefore cost of applied fertiliser can be significantly influenced by the condition of the soil and the performance of the pasture. The condition of the soil can have a major effect on fertiliser use efficiency, including the N and P conversion factor, i.e. the N and P captured in production going from the farm. For example, poorly aerated and waterlogged soils reduce plant available nitrate-nitrogen (NO_3^--N) to nitrite (NO_2^-) and N_2 gas, and sulphate-sulphur (SO_4^{2-}-S) to sulphite (SO_3^{2-}) and sulphides, rendering the N and S unavailable to the plant. The N cycle also cannot work if the S cycle is not working, i.e. plants need sulphur in sulphate form to utilize N. It is partly for this reason that farmers commonly apply more N and S than would otherwise be the case in an attempt to overcome the losses incurred by the chemical reduction effect of soils in poor condition.

Poorly aerated and waterlogged soils also decrease the uptake of phosphorus by pastures. Degraded soils with relatively high Olsen P levels (40–50 mg/L) can show a positive pasture production response to applied P. Moreover, plant uptake of Cu and Co is suppressed when the soil is waterlogged and anaerobic. Again, to boost production, farmers will often apply more phosphorus and trace elements than normally would be required in order to mitigate any nutrient deficiencies.

Do you use fertiliser to grow the plant, or do you use fertiliser to feed the soil to grow the plant?

PLATE 42 **Farm with low production costs**

Farm with on-going low production costs to maintain its current stock-carrying capacity of 3.4 cows per ha.

PLATE 43 **Maintenance application of fertiliser**

Photo: Courtesy of Robert Tucker

TABLE 9 **How to score production costs to maintain stock-carrying capacity**

Visual score (VS)	Production costs
2 [Good]	Production costs have not increased. Only maintenance fertiliser applications required to maintain stock-carrying capacity.
1 [Moderate]	Some additional costs required to maintain stocking rates including some additional fertiliser.
0 [Poor]	Significant additional costs required to maintain stocking rates including significant additional fertiliser.

PLATE 44 **Use of feed supplements**

Feed supplements such as maize silage, wholecrop cereal silage, palm kernel, etc., are often used not only to overcome feed shortages but also to provide an adequate diet of low crude protein and high soluble carbohydrates and starch that are deficient in poor quality pastures.

PLATE 45 **Artificial aeration**

Photo: Courtesy of James Engineering

Ameliorating poorly aerated, compacted soil by artificial aeration.

In addition to soil fertility issues, soils in poor physical condition can have a significant effect on pasture production. Pasture production can recover almost completely within approximately 6 months if the soils are only moderately compacted by stock treading and wheel traffic. Severe compaction and pugging, and the subsequent increase in root penetration resistance and loss of soil structure, porosity, aeration, root length density, and water-holding capacity can reduce dry matter production by up to 40–45 percent. The soil can also take years to recover. If feed utilisation ratios are around 0.7, this decline in pasture uptake would reduce potential stock numbers by 10–20 percent. To offset this trend, additional fertiliser is often applied to maintain dry matter production and stock numbers.

The application of fertiliser can be reduced or kept to maintenance levels if the soil is maintained in good condition. Such conditions includes having good soil aeration with good structure, porosity, root length and root density, good levels of soil carbon, and good soil life in terms of the amount, activity and diversity of soil microbes and earthworms. Keeping your soils in good condition can have a significant effect on keeping production costs to a minimum.

Compacted, poorly aerated soils can be ameliorated by artificial aeration. Aerating the soil can increase dry matter production by 33 percent after 6 months and by 52 percent after 8 months. To minimise the effects of root-pruning and maximise root development, compacted soils should be artificially aerated in the autumn just prior to, or during the root development cycle of the pasture, and when transpiration and respiration demands on the plant are lower than in the spring and summer. Soils should also be aerated when they are moist and sufficiently crumbly to give maximum fracturing (Plate 46) and a smooth surface finish behind the aerator (Plate 45). This can be achieved by using the 'worm test' (Plate 47). Spending money on diesel instead of fertiliser to aerate compacted soils will often give better pasture production and pasture quality.

PLATE 46 **Aerating in the autumn at the optimum water content for maximum results**

Photo: Courtesy of James Engineering

Artificial aeration of compacted topsoils must be timed correctly in the autumn to cause maximum fracturing and minimum disturbance of the surface.

PLATE 47 **The 'worm test'**

For **silty soil**, if you can roll a worm 10 mm wide x 40 mm long between the palms of your hands (7 mm x 40 mm for **clayey soils**) without it cracking, the soil is too wet to aerate. If the worm cracks when it is 10 mm wide for silty soils (7 mm wide for clayey soils), the soil is ready to aerate.

The amount of feed supplements grown and brought onto the farm not only affects production costs but also provides an indication of the ability of a farm to grow grass and quality pasture. Feed supplements such as maize silage, wholecrop cereal silage, palm kernel, etc., are used not only to overcome feed shortages but also to provide the necessary diet of low crude protein and high soluble carbohydrates and starch. These dietary components are deficient in poor quality pastures but are a feature of high quality pasture. The amount of supplements used could therefore be appreciably reduced by simply improving pasture quality – thereby significantly reducing costs.

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.

ISBN 978-92-5-105941-8

9 789251 059418

I0007E/1/08.10

VISUAL SOIL ASSESSMENT

FIELD GUIDE

part 2

Pastures

Visual indicators of environmental performance under pastoral grazing

A GUIDE

BioAgriNomics

Università degli Studi di Teramo

FAO FIAT PANIS

FIELD GUIDE

VISUAL SOIL ASSESSMENT

Pastures

Visual indicators of environmental performance under pastoral grazing

A GUIDE

Graham Shepherd, *soil scientist*,
BioAgriNomics.com, New Zealand

Food and Agriculture Organization of the United Nations
Rome, 2010

ISBN 978-92-5-105941-8

Contents

List of figures

List of plates

Acknowledgements

Text, photographs, plates, tables and figures are reproduced from the original publication: **Shepherd, T.G.** 2009. *Visual Soil Assessment. Volume 1. Field guide for pastoral grazing and cropping on flat to rolling country*. 2nd edition. Horizons Regional Council, Palmerston North, New Zealand, 119 p. with permission from Horizons Regional Council and BioAgriNomics Ltd.

This publication is funded by FAO.

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

1. 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.

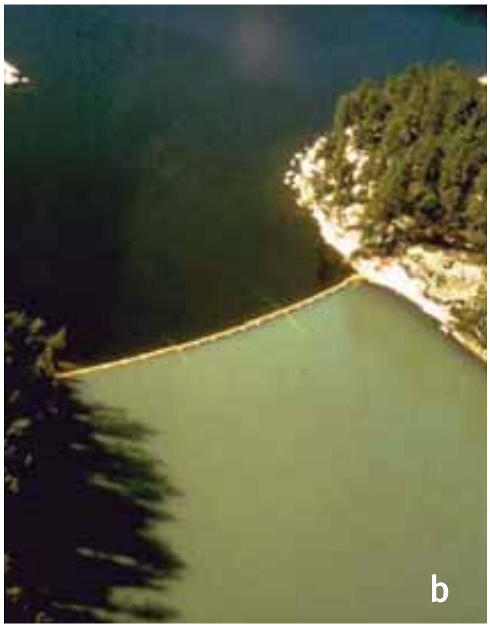
Importance

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.

[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]

carbon sequestration

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).

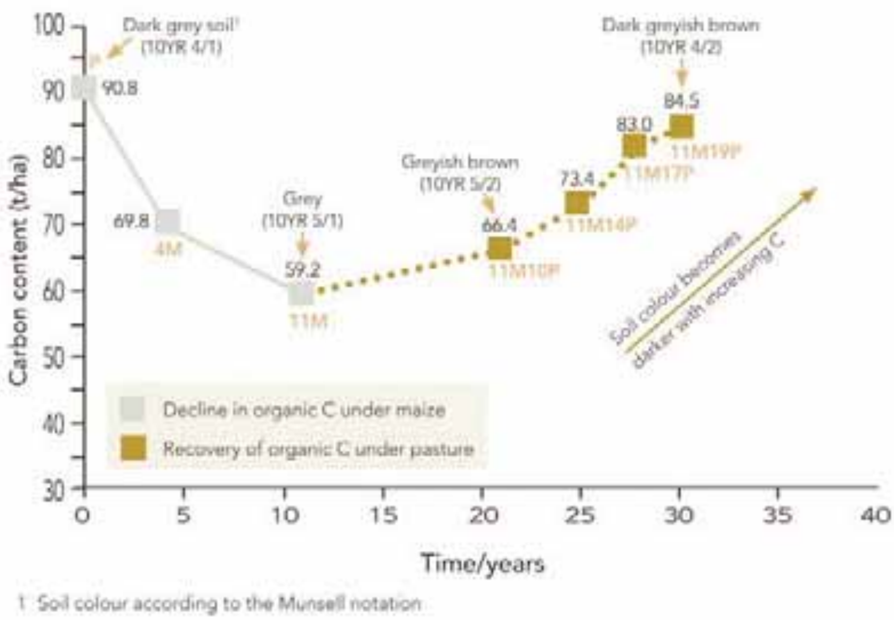
carbon sequestration

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**



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

1. 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.

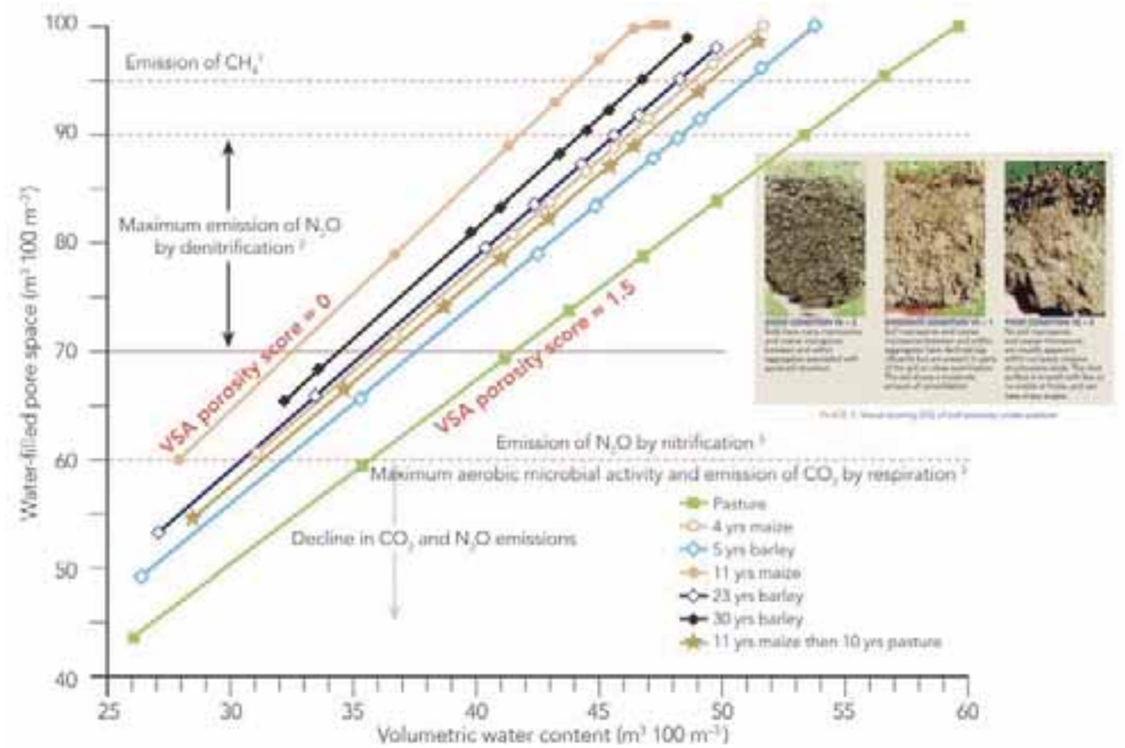
While CO_2 is a major GHG, it is reabsorbed as photosynthate by plants and can therefore be greenhouse neutral. Most atmospheric methane is also removed by photochemical oxidation, inactivated by the hydroxyl (OH) free radical in the atmosphere. In addition, methane is inactivated by oxidation in aerated, 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.

ISBN 978-92-5-105941-8

9 789251 059418

I0007E/1/08.10

FIELD GUIDE

VISUAL SOIL ASSESSMENT

part 1

Maize