Soil Organic Matter in the South Island High Country

A.E. Hewitt and P.D. McIntosh

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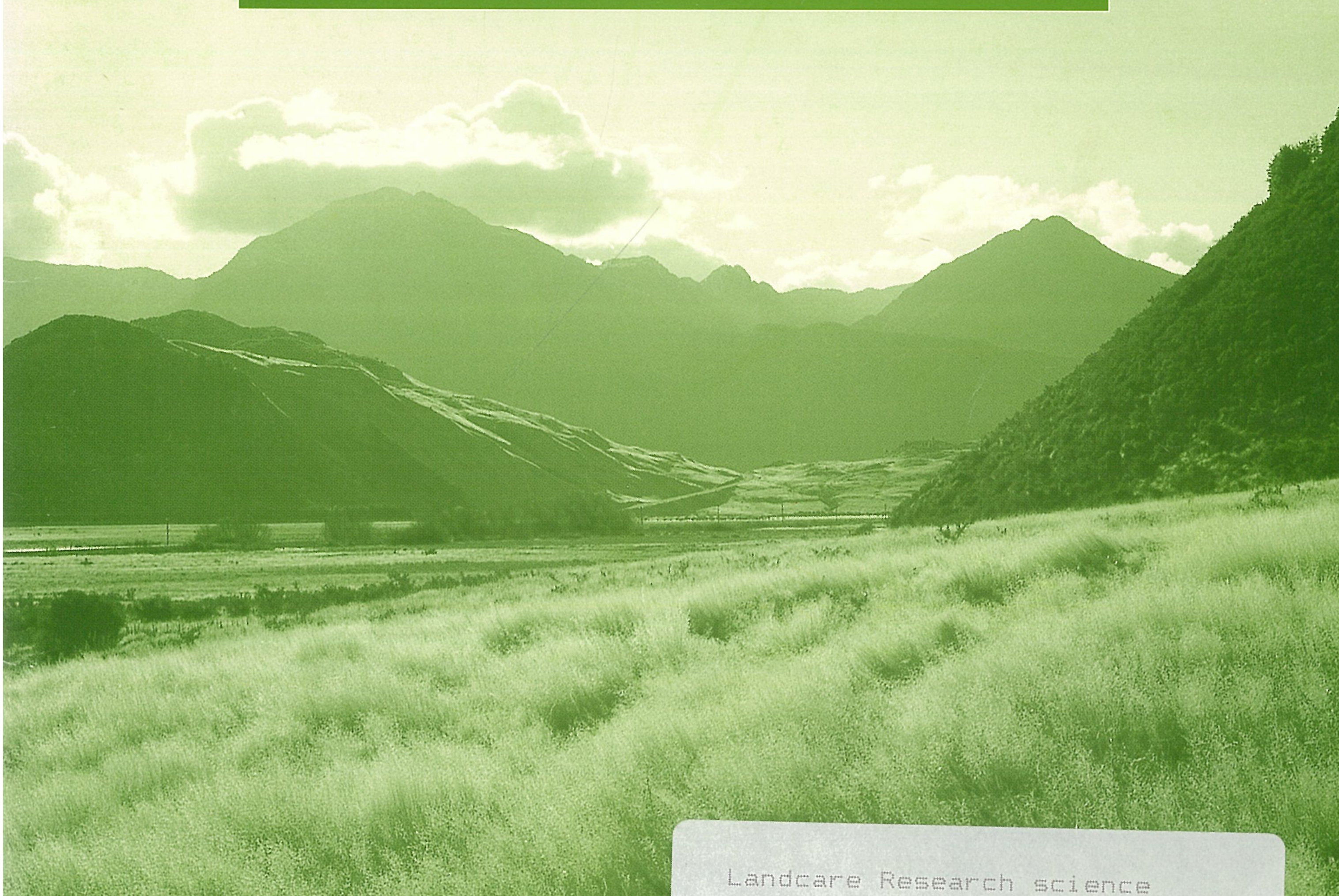

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Cover:
View of typical South Island high country. Good soil organic matter management is required on both the pastoral hills and steeplands as well as the arable basin floors.

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1. Introduction

Soil organic matter has received increased attention in recent years because it has become widely recognised as a critical and relevant soil component for sustainable management of soils, including those of the South Island high country. The final report of the Working Party on Sustainable Land Management (Martin *et al.* 1994) drew particular attention to evidence for decline in soil organic matter, particularly in the drier unimproved lands. It was recommended that "a concerted effort be undertaken to raise the awareness of land holders, and all relevant institutions, of the likely impact of pastoral land-use and rabbit infestations on the soils of the high country."

It is the aim of this book partly to fulfil this recommendation by increasing the understanding of soil organic matter in high country soils and to provide a sound basis for land management and monitoring of land use impacts.

This is not a detailed text book on soil organic matter (see McLaren and Cameron 1990). It should be regarded as an introduction that will facilitate further informed enquiry. Much is still unknown and it is hoped that increased dialogue between land managers, policy makers and scientists will help focus further research.

The scope of this book is restricted to the high country tussock grasslands and herb fields that are, or have been, used for grazing. It does not directly address the soils of high country forested lands and alpine lands.

2. Soil condition

2.1 Soil condition and erosion

Soil degradation occurs in essentially two ways: by **soil erosion** and by **loss of soil quality**[1] **or condition.**

Although soil erosion is a legitimate concern it can be argued that it is more important to focus on loss of soil condition than on erosion. This is because accelerated erosion is frequently the consequence of poor soil (and vegetation) condition. To use a stock management analogy, the farmer is concerned to recognise early signs of ill-thrift in his stock. Focusing all attention on erosion is like managing stock health by monitoring death rates. We must learn to recognise the early signs of ill-thrift in topsoils before the soils erode.

2.2 A comprehensive check-up of soil condition

A comprehensive check-up of soil condition would require the evaluation of many qualities in the soil. The most important of these can be grouped conveniently into the three categories shown in Figure 2.2.

Evaluating all these qualities would require a great deal of work and expense. Some, for example erosion status, may only be evaluated at a few sites. For this reason a short list of qualities needs to be chosen which, while not providing a comprehensive evaluation of soil condition, will provide a good indication. These are called soil indicators. Further information on soil indicators is provided in section 6.3.

2.3 Importance of soil organic matter

Soil organic matter is an important component of the soil because it has beneficial effects on biological, chemical and physical systems in the soil.

Biologically, soil organic matter (including plant residues) is the source of energy for soil micro-organisms (or microbes). Microbes are the 'engine' that drives the cycling of nutrients within the soil.

Chemically, soil organic matter is a major reservoir of plant nutrients. It is the major source of plant nitrogen, sulphur and phosphorus which are cycled through accumulation and decomposition of soil orgainc matter. Other nutrients such as calcium, magnesium and potassium are loosely attached as cations to negatively charged bonding sites on soil organic matter and are released into the soil solution when these nutrients are absorbed by plants or lost by leaching. Nutrients are lost when soil organic matter is lost through erosion or when soil organic matter levels decline because mineralisation (decomposition) becomes greater than accumulation.

Physically, soil organic matter stabilises soil structure and soil pores and therefore has a marked effect in enhancing structural stability, aeration and infiltration of rainfall. Soil organic matter also enhances water storage capacity.

The prime role of organic matter varies between soils in different environments. For example, in the more fertile soils of the semi-arid basins soil organic matter is important for soil water storage capacity and water infiltration, whereas in the wetter high country its role in storing and making nutrients available to plants is more important.

2.4 Using soil carbon to estimate soil organic matter

The amount of soil organic matter in the soil is not easily measured. However, carbon is a major component of soil organic matter and may be precisely measured. The amount of carbon is therefore routinely used to estimate the amount of soil organic matter.

Soil organic matter content is estimated by the following formula:

Soil Organic Matter (%) = 1.7 x Soil Carbon (%)

1 *Soil quality has been defined as "The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran et al. 1994)*

Biological condition

1. There are sufficient worms and other soil animals to aerate the soil and break up and incorporate dead plant material into the soil.

2. The population of microbes is sufficiently large and active to recycle nutrients from dead plant material.

Chemical condition

3. There are sufficient major and minor nutrients immediately available to plants and held in reserve to meet short term and long term nutritional needs of plants and animals.

4. The level of acidity is not more than the desired plants can tolerate.

5. Toxic elements or compounds are not present in sufficient concentrations to limit soil biological processes and plant growth.

Physical condition

6. Soil structure is sufficient to maintain good water infiltration, water storage, air supply to plant roots and good root penetration.

7. Surface cover (either litter or plant cover) is present in sufficient quantities to insulate the soil from temperature extremes and protect it from erosion.

8. There is no accelerated erosion.

Figure 2.2.
Qualities of a soil in good condition

Carbon can also occur in the soil mineral fraction, particularly in soils that have formed from rocks containing calcium carbonate, such as limestone. In the South Island high country such soils are rare and it can safely be assumed that measured total carbon is solely from soil organic matter. Thus, for most soils, figures reported as "organic soil carbon" and "total soil carbon" will be very similar.

Routine total carbon analysis is done at the Landcare Research analytical laboratory at Massey University, Palmerston North, using the high-frequency induction furnace method. Results have high accuracy and are reported to the nearest 0.01%. The soil testing service of the AgResearch soil and plant testing laboratory at Invermay, Mosgiel, uses the dichromate oxidation method and report accuracy to the nearest 0.05%. More specialised analyses are used to determine carbon associated with the microbial fraction. These techniques are also well established in New Zealand. A number of other commercial laboratories also do soil carbon analyses.

The carbon content of the soil is most frequently expressed as the weight of carbon per weight of soil (usually grams of carbon per 100 grams of soil and reported as a percentage) but it may also be expressed as weight per volume of soil. This requires that the carbon be analysed in a sample of known soil volume. The result is reported as either kg/ha or tonnes/ha for the thickness of the topsoil or to some specified sampling depth. The sampling depth, as for most soil fertility sampling in pastures, is usually 0 - 7.5 cm. In this report this depth is assumed unless specified otherwise.

3. Overview of High Country soils

3.1 Soils at a regional scale

In the high country the most common soil orders[2] are Brown Soils, Pallic Soils and Semiarid Soils[3]. These are distributed in a regional pattern (Figure 3.1a page 17) related to climate. **Semiarid Soils** are in basins and basin margins where rainfall is less than about 500 mm/year (Figure 3.1b page18). **Pallic Soils** occur in moister regions (about 500–800 mm rainfall) that have a distinctly dry summer (Figure 3.1c page 19). **Brown Soils** are in areas of higher rainfall (mainly over 800 mm/year), either closer to the main divide or at higher altitudes where soil water deficits are uncommon in summer (Figure 3.1d page 20).

The Brown Soils are the predominant soils of the high country. Three groups of Brown Soils are common.

Soil Order	Soil Group
Brown Soils	Allophanic Brown Soils Acid Brown Soils Orthic Brown Soils

The **Allophanic Brown Soils** are dominated by highly reactive stiff jelly-like clay minerals (allophanic minerals) comprising iron and aluminium oxides and hydroxides that have a very high affinity for phosphate. They have high organic matter concentrations in the topsoil, but low concentrations of basic cations (calcium, magnesium, potassium and sodium). The soils have strongly developed crumb structure and are highly permeable. They are mostly confined to higher altitudes and frequently on steep slopes.

The **Acid Brown Soils** are very strongly acid (pH 4.8 or less). Topsoil organic matter contents are usually high and, like Allophanic Brown Soils, they have very low contents of basic cations. Some of the Acid Brown Soils have a thin iron pan that restricts drainage. The soils occur most frequently at higher altitudes.

The **Orthic Brown Soils** are ordinary Brown Soils that do not have significant allophanic minerals or very strong acidity. They generally have lower organic matter contents in topsoils, and higher amounts of basic cations, than the other Brown Soils. They are more common at the lower altitude range of Brown Soils or on younger or less stable landforms.

Three other important soil orders (Gley, Recent and Organic Soils) occur in association with the Semiarid, Pallic, and Brown Soils. (Figure 3.1e). **Gley Soils** occur in parts of the landscape that have high watertables. These might be in low parts of the landscape or on slopes where there are seepages of water. **Recent Soils** are weakly developed either because they are on young land surfaces, on erosion scars or sediments deposited by floods, or on sites where rock occurs at shallow depths. **Organic Soils** are developed in peat. They occur more frequently at higher altitudes, either in wet hollows, or on hill crests or slopes where drainage is restricted and precipitation is high.

Semiarid Soils generally have the lowest carbon contents, followed by Pallic Soils and Brown Soils (Figure 3.1e). This sequence reflects increasing rainfall.

2 *Soil classes are recognised in a hierarchy in which soil orders are the highest level. There are 15 soil orders recognised in New Zealand. The soil orders are subdivided into soil groups and these, in turn, are subdivided into soil subgroups. Soilforms and soil series are recognised within subgroups.*

3 *These names are defined in the New Zealand Soil Classification (Hewitt 1993). Brown Soils are broadly equivalent to yellow-brown earths, Pallic Soils are broadly equivalent to yellow-grey earths and Semiarid Soils are broadly equivalent to brown-grey earths of the New Zealand genetic soil classification (Taylor & Pohlen 1962).*

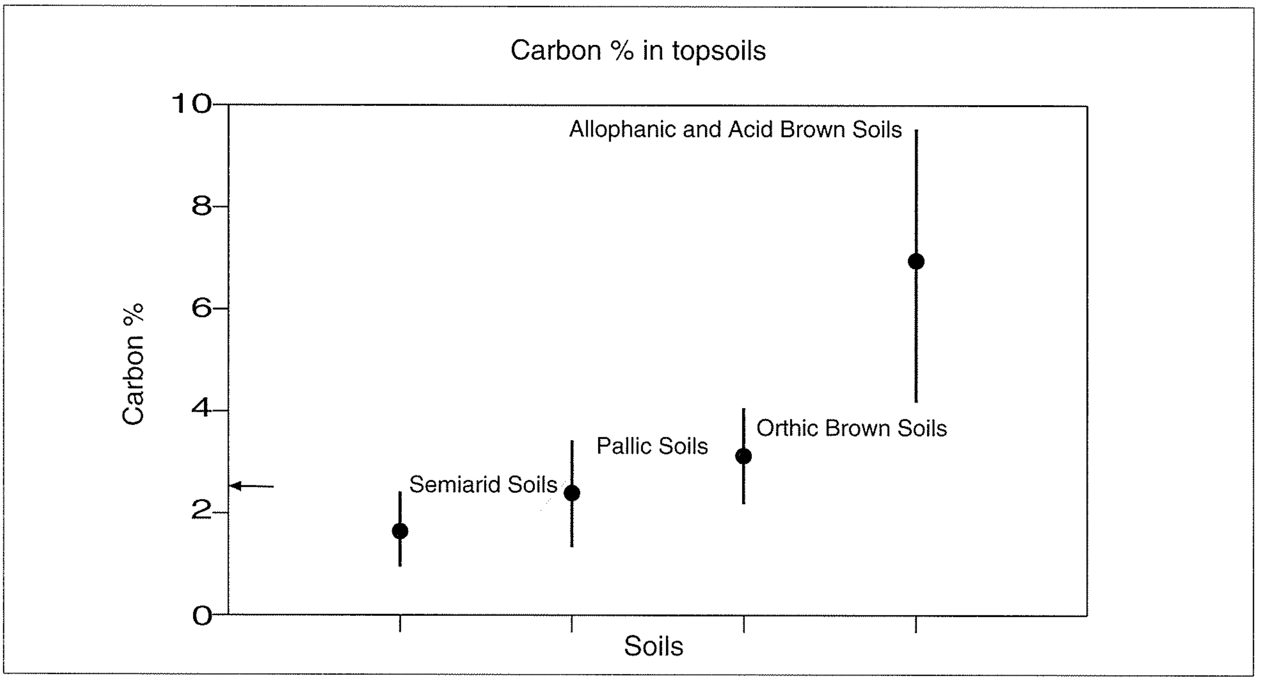


Figure 3.1e
Percent carbon in topsoils for Semiarid Soils, Pallic Soils, Orthic Brown Soils and Allophanic and Acid Brown Soils. The data is from the National Soils Database and shows means and standard deviations. The arrow indicates the critical level of concern, below 2.5%. Soil organic matter quantity is more likely to be an issue in the Semiarid Soils and Pallic Soils than in the Brown Soils. See sections 6.3 and 7.

3.2 Soils at a local scale

Superimposed on the regional soil pattern are local variations. These are strongly related to landforms.

Ridge-valley variation

Variations in soil depth with topography are illustrated in Figure 3.2a (page 10). Shallow soils occur on ridges and upper sideslopes, particularly on sunny aspect sideslopes (Figure 3.2b page 11). Soils on lower sideslopes are generally deeper. Soil organic matter levels are usually higher on shady aspect slopes relative to sunny aspect slopes.

The slopes where soils are shallowest are usually sites where potential for surface soil erosion is greatest.

3.3. Further information

Reasonably detailed district soil surveys have been made of many of the basin floors in the South Island high country. These may be obtained through any Landcare Research Office (or by writing either to Manaaki Whenua Press, P.O. Box 40, Lincoln, or Department of Survey & Land Information, P.O. Box 170, Wellington). Other areas not covered by district soil surveys are included in the broad scale General Survey of Soils of the South Island (NZ Soil Bureau 1968) and the New Zealand Land Resources Inventory (NZLRI). Relevant publications are listed in the bibliography.

Other texts that provide background information on New Zealand soils include "Soils in the New Zealand landscape" by Molloy (1988) and "Soil Science" by McLaren and Cameron (1990).

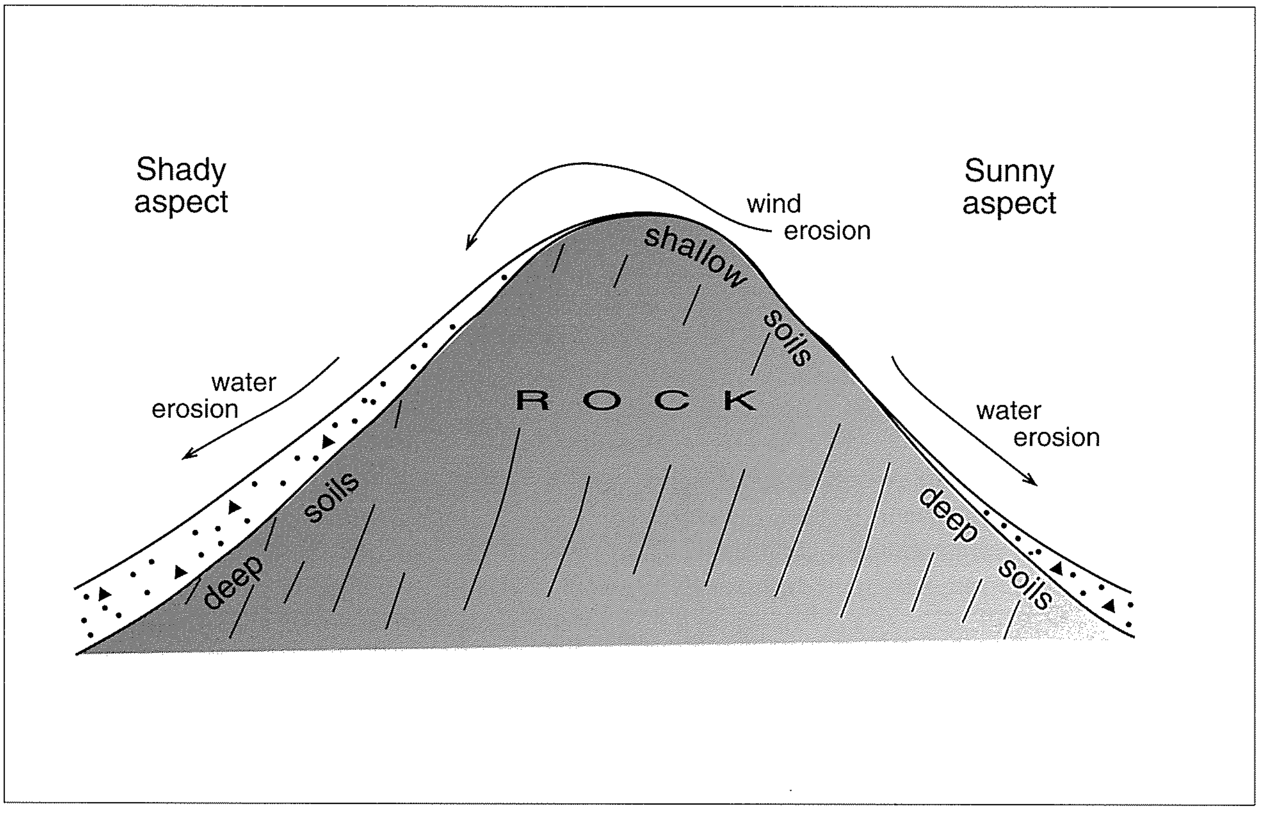


Figure 3.2a

A common pattern of soil variation occurs across ridges, from major mountain ridges to minor spurs. Shallow soils with relatively low available water holding capacity are more common on ridges and spurs and on upper slopes of sunny aspect slopes. These shallow soils, except where there are stock camps, and soils on sunny aspects usually contain lower soil organic matter than soils on shady aspects. They are the soils most at risk. See Figure 3.2b.

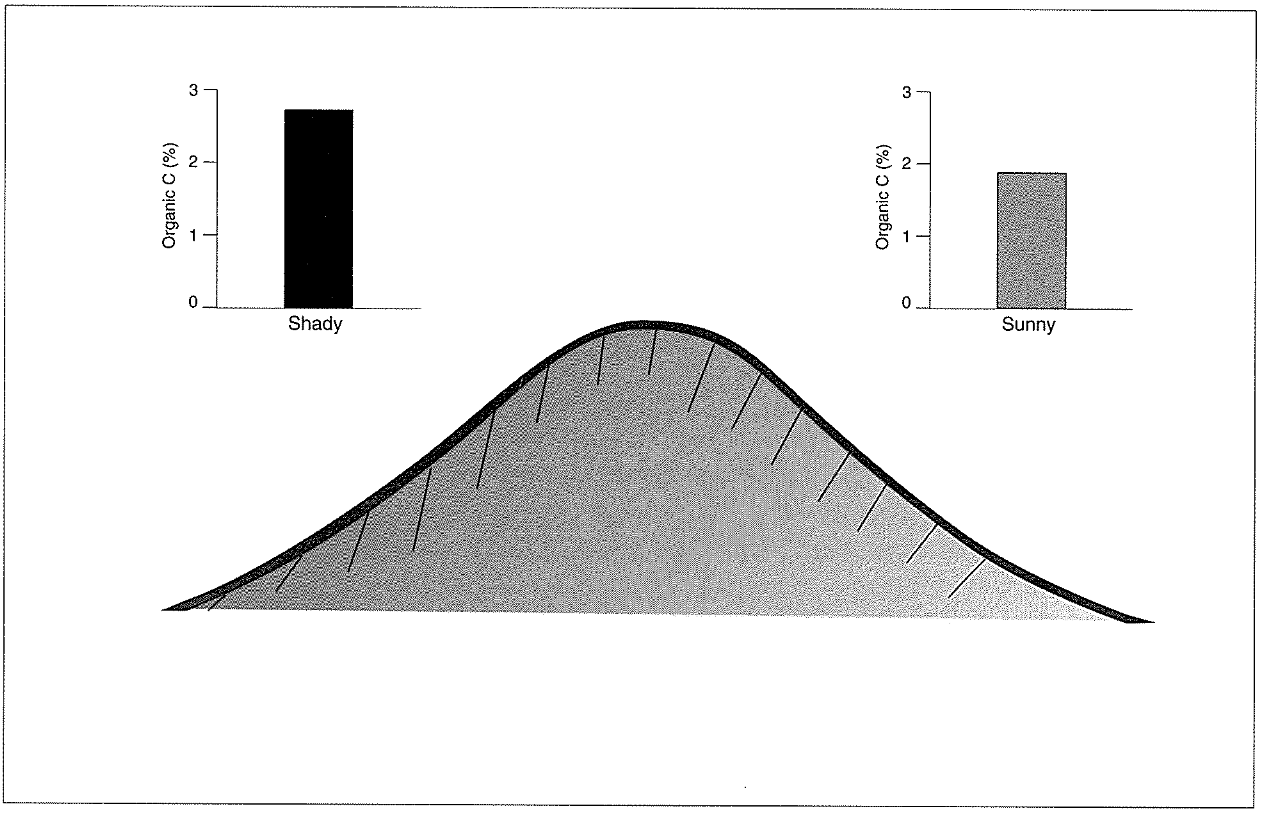


Figure 3.2b. Case study

The effect of aspect on soil carbon levels at 0-7.5 cm depth was measured in a 1978 survey of a ridge on Glencairn Station, on the Benmore Range, in the Upper Waitaki. Soils are mainly Recent Soils, with some Pallic Soils. The results shown are the mean of 12 sites on each aspect. Percent carbon in topsoils is 0.8% higher on shady slopes. Standard Error of the Difference = 0.2.

4. The nature of soil organic matter

Soil organic matter is a complex mix of living, dead and decomposing material (Figure 4) intimately associated with inorganic compounds.

The living component consists of soil animals, plant roots and micro-organisms. Although this component is a small part (rarely in excess of 5%) of the total organic matter, it is very important for nutrient cycling.

The soil animals include:

- live root feeders
- live plant-leaf feeders
- organic matter feeders living on dead leaves, roots, wood and micro-organisms
- predators feeding on other animals.

Worms are the dominant group of soil animals under pasture. They play a vital role in aerating the soil and intimately mixing organic topsoil with mineral layers in the subsoils, thereby accelerating nutrient cycling. In many soils the total weight of earthworms in a given area may be equivalent to several times the weight of grazing animals on the same area.

Soil micro-organisms are microscopic in size and include:

- algae which can make sugars by photosynthesis
- fungi (including yeasts) which are effective at rotting damp plant fragments
- bacteria which decompose most organic (and many inorganic) compounds and in some cases transform atmospheric nitrogen into plant available forms
- actinomycetes which also decompose organic material
- protozoa that prey principally upon bacteria and algae
- nematodes that feed on roots, and other soil organisms.

In fertile pastures the total weight of micro-organisms is similar to the total weight of 10 rugby teams on the area of a rugby field.

Plant residues are finely divided plant fragments: the left-overs remaining from the feeding of soil animals and micro-organisms.

Humus is the dark-coloured, relatively stable product of many microbial transformations of plant fragments, soil animal bodies and waste products. It plays a very important role in soil water storage, cation exchange and stabilising soil structure. Further information on the role of soil organic matter is available in McLaren and Cameron (1990).

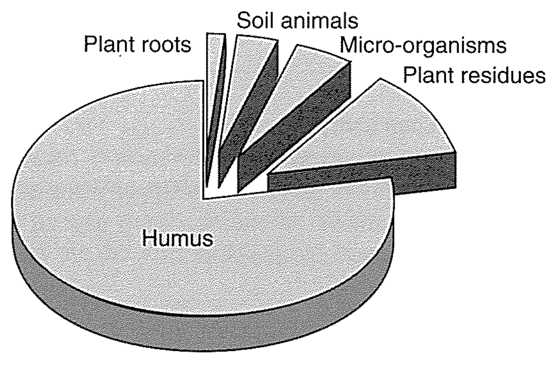


Figure 4
Composition of soil organic matter by % carbon. The plant roots, soil animals and micro-organisms (microbial) components are all living. The plant residues and humus components are dead matter.

5. Principles for soil organic matter management

Six principles are presented as a basis for soil organic matter management. These are the basis of the management guidelines given in Section 7 (page 30).

5.1 The quantity of soil organic matter is controlled primarily by plant growth

The quantity of soil organic matter in the soil is primarily the result of a balance between inputs and outputs. These are illustrated in Figure 5.1.

Vegetation has a major direct influence on soil organic matter levels through litter decay, roots and chemicals produced by the roots (root exudates) and an indirect influence through dung deposited by grazing animals. The quantity of inputs, therefore, depends upon plant productivity. In grasses, including tussock, the productivity of roots is particularly important for the maintenance of soil organic matter.

Soil organic matter is produced by the decay of plant litter, death and decay of plant roots, and release of chemicals from living roots (root exudates). The process of decomposition is driven by large numbers of living organisms (soil biomass). These range from soil animals that physically break down litter into smaller portions and incorporate it into the topsoil, to bacteria and fungi that complete its decomposition.

Losses of soil organic matter occur by production of gases released into the atmosphere and chemicals leached by drainage water. Carbon dioxide (CO_2) gas is the predominant substance lost. The rate of organic matter decomposition increases with increased temperature and with the availability of sufficient water and nutrients. Losses are also caused by the removal of vegetation by grazing or burning. Organic matter that would otherwise have been contributed to the soil is exported in the bodies of animals sent off the farm or transferred elsewhere, e.g., to stock camps.

The quantity of soil organic matter can be increased by either increasing inputs or decreasing losses. Because loss rates depend upon soil temperature and water, they can be changed only by irrigation, changes in vegetation canopy or litter cover. The only means of raising the quantity of soil organic matter is by raising net inputs: that is, by raising plant productivity. **Vegetation management is a key to soil organic matter management.**

Soil organic matter is composed predominantly of carbon, oxygen, hydrogen, and smaller amounts of nitrogen, sulphur and phosphorus, and trace elements - in fact the same constituents as in plants and animals. Carbon, oxygen and hydrogen comprise the basic framework of organic matter and come ultimately from the atmosphere. These elements cannot be added as fertilizer. In order to build up soil organic matter, they need to be added to the soil in the form of plant or animal tissue. The alternative to growing plants on-site to build up soil organic matter is to spread manure derived from plants grown off-site but this is not practicable for large areas of extensively grazed high country.

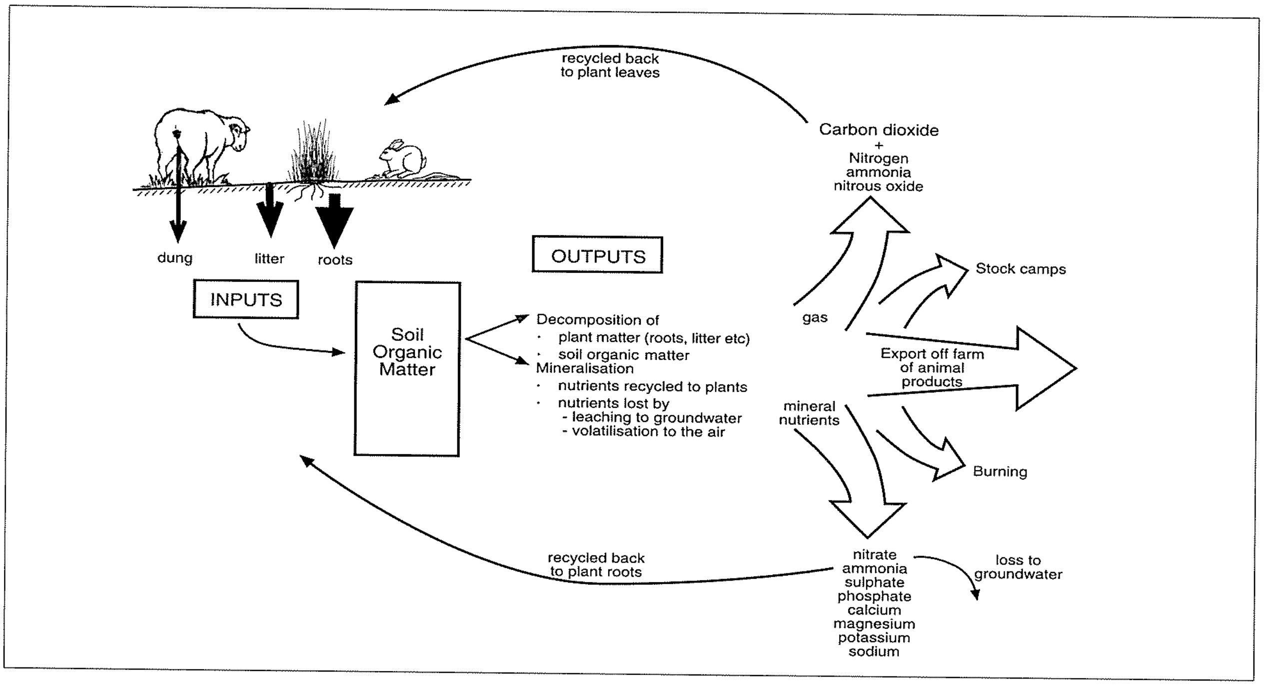


Figure 5.1

Organic matter inputs to the soil include mainly litter fall from growing plants, root growth, chemicals released by roots (root exudates), and dung and urine from animals. Losses (or outputs) of soil organic matter occur mainly through (1) decomposition causing release of carbon dioxide gas and other trace gases to the atmosphere and (2) mineralisation enabling recycling of nutrients back to the plant or loss in leaching water or volatilisation of gases. Plant growth is the major control on soil organic matter content.

5.2 Grazing animals pre-decompose organic matter and transport it

Animals graze vegetation at one site and deposit dung and urine at a different site. In closely subdivided areas where grazing density is high, there is a relatively uniform return of dung and urine within the paddock over time. In hill country areas, where grazing density is low, there is very uneven redistribution of organic matter through the grazing animal. About half or more nutrients consumed by the animal may be concentrated within very small areas, called 'stock camps' (Figure 5.2a). Transfers also include removal of organic matter from the farm in animal carcases. These transfers intercept inputs to the soil and, if significant, may lead to reduced soil organic matter levels.

Another effect of grazing is to reduce the amount of plant litter available for decomposition in the soil. In general, soils that are frequently heavily grazed have low quantities of plant litter lying on the soil surface. Decomposition of litter provides a relatively evenly distributed and steady supply of organic carbon to the soil (although the contribution of carbon by root growth is probably greater[4]). Another important function of litter is to shade the soil surface and thus reduce loss of water from evaporation and reduce maximum summer soil temperatures. High soil temperatures, associated with low plant and litter cover, increase mineralisation rates and thus further decrease soil organic matter levels. During winter, litter insulates the soil against freezing. Litter also helps to protect the soil from erosion.

4 *Although root growth is an important source of soil organic matter, root production is linked to above ground production. Grazing of the above ground plant will cause reduction or cessation of root growth as the plant transfers stored nutrients from roots to grow new shoots. The relative contributions from roots and above ground plant residue has not been precisely measured.*

Dung and urine is deposited in a partly decomposed form that may be incorporated by the mixing effect of soil animals into the soil. Grazing therefore has the effect of increasing the rate of organic matter cycling. This is not a problem if plant inputs are high but if they are not then the net loss of soil organic matter is promoted. Unfortunately, the return of organic matter as dung and urine to the soil is inefficent because it is concentrated in patches. Losses of nitrogen occur in the patches through evaporation and leaching (Figure 5.2).

The net effect of grazing on the soil is not yet clearly understood but is likely to depend more on the productivity of the vegetation than on the animals themselves. If grazing reduces vegetation production, soil organic matter levels are likely to be lowered even if they become rapidly incorporated into the soil and transfers or concentrations of dung and urine are minimised.

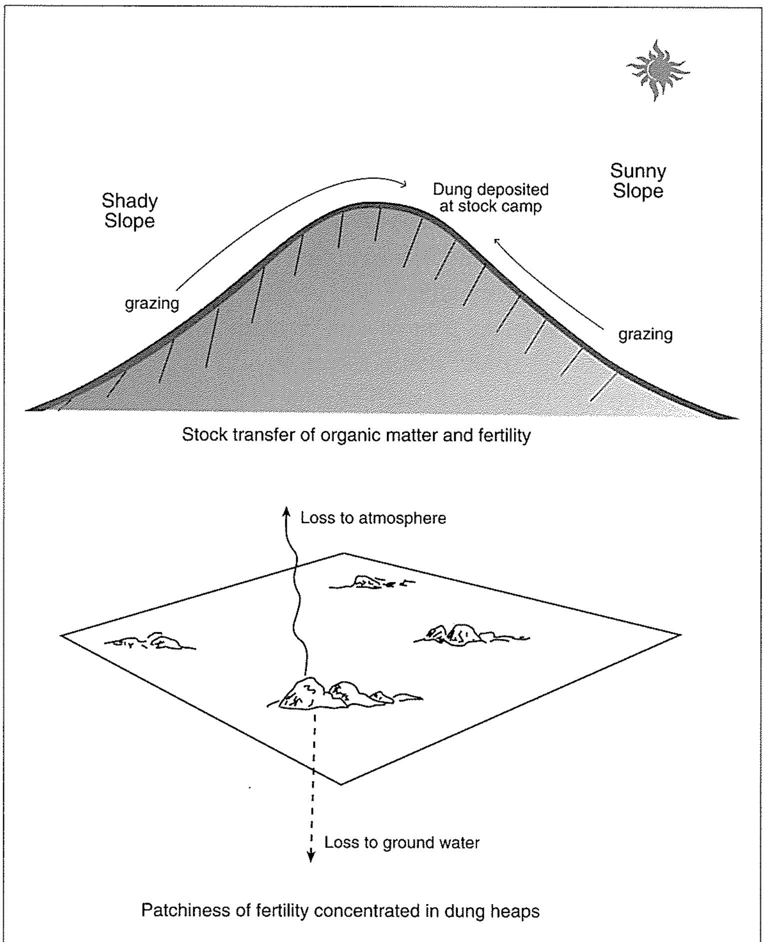


Figure 5.2
Grazing animals have the effect of pre-decomposing organic matter before addition to the soil. They also strongly affect its distribution causing patchiness of fertility and transfer of fertility to stock camps (often at sunny warm sites).

5.3 Changes occur very slowly towards steady state

Soil carbon levels (i.e. organic carbon levels) are determined by the balance between losses due to decomposition and removals or transfers by animals, and inputs from plants by decay of roots, production of root exudates and litter. Losses due to decomposition depend mainly on soil moisture and soil temperature and the type and content of soil clay. The degree to which decomposition is affected by management is not well known. Inputs from plants, however, are highly dependent on vegetation management, and vegetation management is the major factor which changes carbon levels.

Initially, when soil formation begins in weathered rock or sediments, organic inputs exceed outputs and the quantity of soil organic matter increases until a balance between inputs and outputs is achieved. The level at which this balance occurs is called the "steady state" (Figure 5.3a), and is determined by the nature of the vegetation, its productivity, grazing removals and returns, soil fertility, soil temperature and soil moisture. It is likely to take several hundreds of years to reach this steady state.

In some sites where the soils are young, carbon levels may be less than expected considering their good vegetation cover. This may be because the carbon is still accumulating and has not approached the potential steady state.

When some intervention by management occurs that affects organic inputs or outputs, soil organic matter quantities will adjust to a new steady state level. Managed soils may never reach a true steady state because there are continual small changes to inputs through grazing, variation in vegetation vigour and species composition, irrigation and fertilizers. Decomposition rates will vary for similar reasons.

Early in the history of grazing in South Island tussock grasslands, plant residue inputs were substantially lessened as the tussock biomass was reduced through burning and grazing. It is not known what the original soil organic matter levels were, but it is probable that current levels in unfertilised grasslands are now much lower. Heavier grazing during rabbit plagues would have further reduced organic matter. In areas of intensive pastoral development soil carbon has increased showing recovery of soil organic matter towards new higher steady state levels (Figure 5.3).

The maximum steady state concentration of carbon that a soil can attain under ideal conditions varies from soil to soil. It depends upon the adequacy of soil moisture and temperature and the amount and type of clay[5]. For example, maximum amounts of carbon in Semiarid Soils are limited by inadequate moisture and generally low clay contents. In contrast, Allophanic Brown Soils may have very high amounts of carbon because the allophanic clay particles have a high affinity for organic matter.

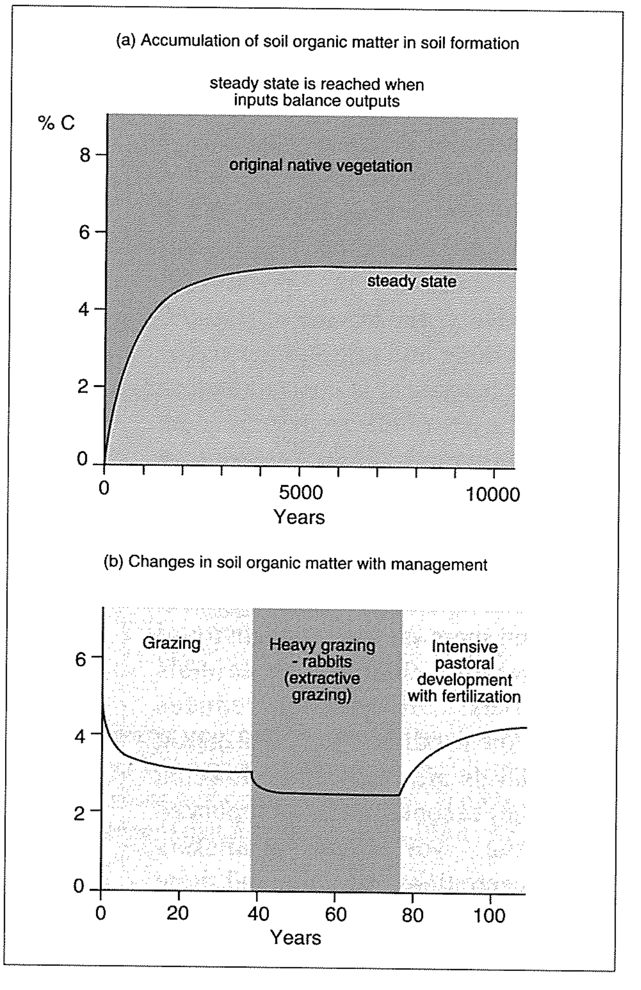


Figure 5.3
When a soil is forming, or recovering from loss of organic matter, inputs initially exceed outputs until a balance is achieved. When a balance is achieved, the soil is in a steady state. When land use causes reduction of inputs, losses of soil organic matter will result because outputs initially exceed inputs. Soil organic matter will continue to be lost until outputs gradually reduce to a rate that balances the lower inputs and a new, lower, less satisfactory steady state is reached. Change towards a new steady state level occurs very slowly.

5 *Clay is more important than silt or sand because the particles have very high surface area and are more chemically active.*

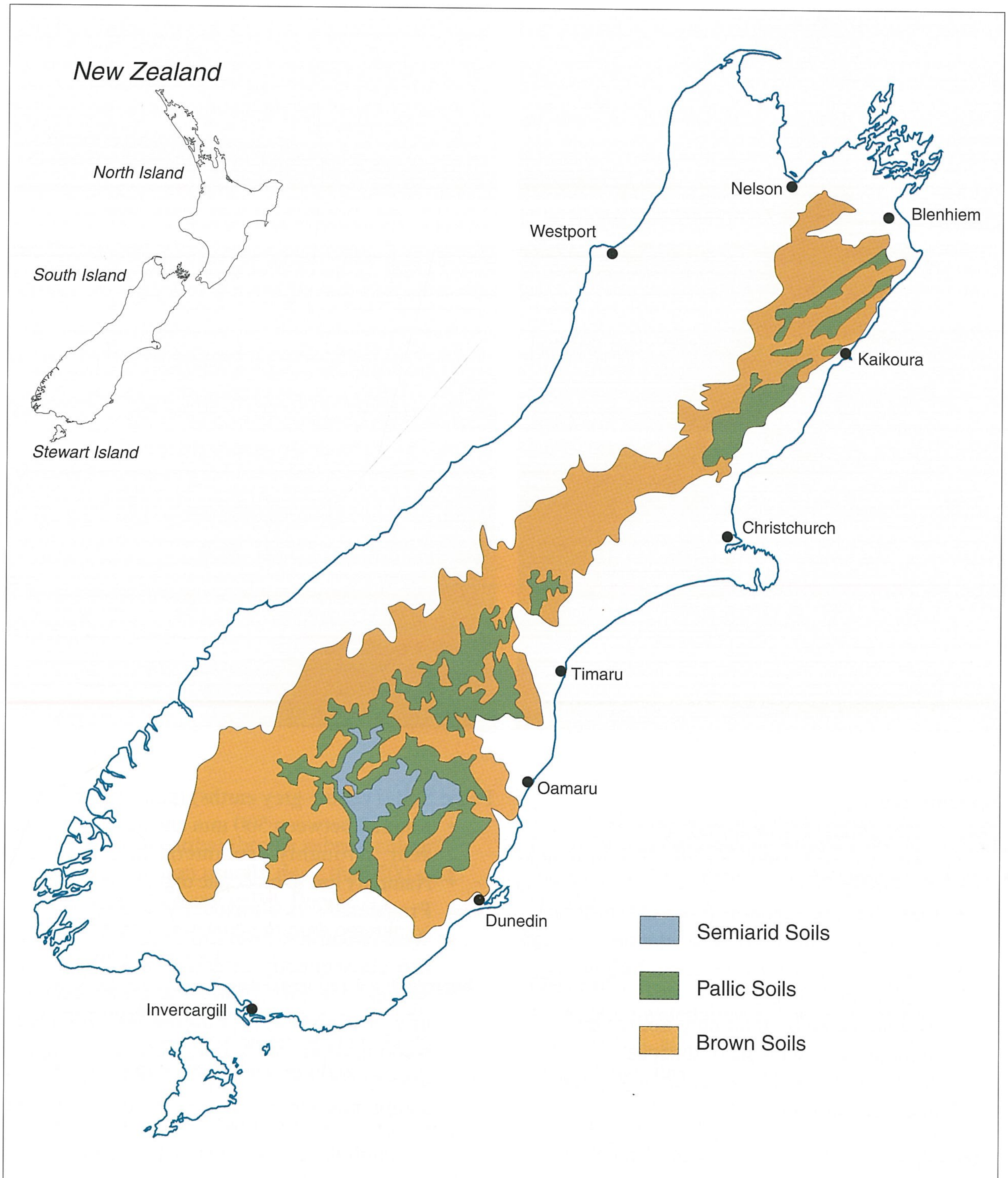


Figure 3.1a
Regional soil map shows the distribution of soils described in Figures 3.1b to 3.1d.

Figure 3.1b

Semiarid Soils
(brown-grey earths) (in semi-arid climate)

- Rainfall less than about 500 mm/year
- Naturally low organic matter contents
- Low CEC and consequently very sensitive to management. Phosphate retention very low
- High fertility, but low reserves. Sulphur is commonly deficient
- Rooting depth is commonly limited by moderate to high density subsoils
- A layer of natural lime commonly occurs in deeper subsoils
- Production is severely limited by water deficits

Pallic Soils (yellow-grey earths) (pale soil colours)

- Rainfall between 500 mm and about 800 mm/year. Droughty summers, moist winters
- Naturally low to moderate organic matter levels
- Production is limited by water deficits
- Weakly buffered with low to moderate CEC and consequently sensitive to management
- Moderate fertility. Sulphur and phosphorus and molybdenum commonly deficient
- Rooting depth and drainage limited by high density subsoils or by rock, except on many steeplands where rooting is not restricted
- Phosphate retention low

Figure 3.1c

Brown Soils
(yellow-brown earths) (brown subsoil colours)

- Precipitation usually more than 800 mm except on stony valley floors
- Naturally moderate to high organic matter contents
- Brown colour due to iron oxides dispersed throughout the soil mass.
  Phosphate retention moderate to high
- Low contents of basic cations
  Commonly acidic
- Rooting depths generally not physically restricted and usually free draining
- Low natural fertility with deficiencies of sulphur, phosphorus and molybdenum.
  Liming is commonly required

The three dominant soil groups of Brown Soils in the High Country (Allophanic Brown Soils, Acid Brown Soils and Orthic Brown Soils) are described in the text, Section 3.1.

Gley Soils

- High watertables at least in winter and early spring, and occurring throughout the year at some sites
- Grey subsoil colours, usually with reddish brown mottles
- High organic matter contents (in topsoils)

Figure 3.1d

Organic Soils

- High watertables throughout the year
- Very high organic matter content
- High total available water capacity
- Common nutrient deficiencies
- Low bearing strength

Recent Soils

- Weakly weathered soil materials
- Low to high organic matter content
- Usually freely draining
- Subject to erosion or sedimentation
- Moderate natural fertility (except sulphur), low at high altitudes
- Deep rooting

5.4 The microbial population strongly influences mineralization and decomposition

Mineralization is the release from soil organic matter of nutrients such as nitrogen, sulphur and phosphorus, in a form that can be taken up by plants. It is achieved by soil microbes that feed on organic matter and excrete and release mineral nutrients, mainly nitrate, sulphate and phosphate. The process is most active close to plant roots, where there is a good supply of available carbon. Although the microbial population is only a small proportion of total soil organic matter, (Figure 4 page 12) it is extremely important. The size and activity of the microbial population is a measure of soil organic matter quality, because it controls many of the processes critical for plant nutrition, particularly the rate of decomposition and release of nutrients.

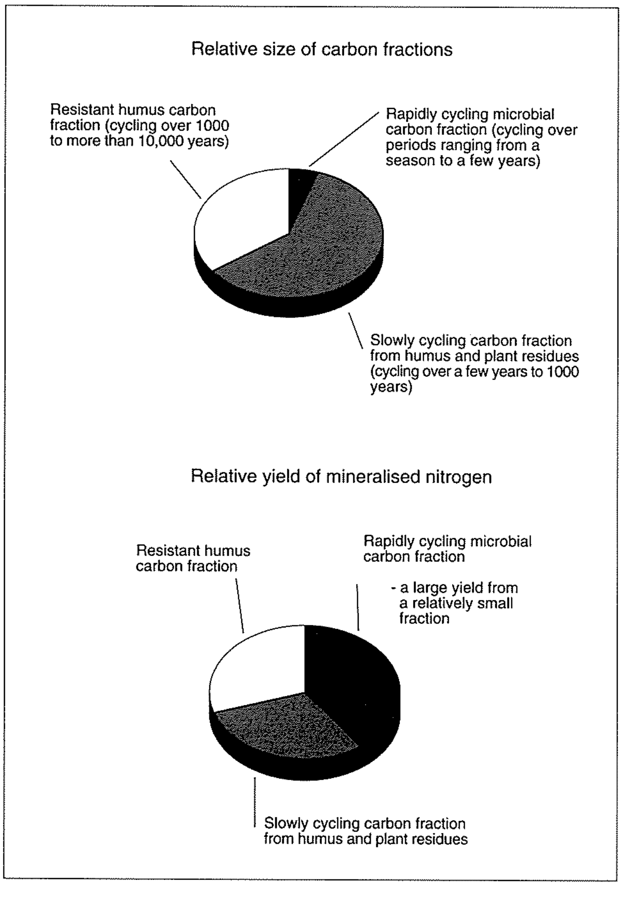


Figure 5.4

Soil organic matter can be divided into fractions (also called "pools"). The different pools contain carbon that is cycled at different rates. The time taken is called "rate of carbon cycling" or "carbon turnover rate". The mineralization part of the soil organic matter cycle releases nutrients from soil organic matter for absorption by plants. When soil organic matter is reduced, the microbial fraction is the first to decline. Because this fraction dominates mineralization the rate of release of nutrients from the whole soil by mineralization is likely to decline. **Microbial carbon is where the action is.**

The cycle of plant death, decomposition, formation of soil organic matter and release of nutrients by mineralisation (Figure 5.1) is called soil organic matter cycling (or soil organic matter turnover). The rate of soil organic matter turnover can be estimated in soils from the cycling rate of carbon in various fractions of the soil organic matter.

Carbon in the microbial fraction of the soil is cycled quickly (from 1 or 2 years to months or weeks). In other fractions carbon cycling rates are much slower. Much of the humus fraction has rates of up to 1000 years and some resistant portions may be recycled over periods of more than 10, 000 years (Figure 5.4). This resistant carbon can be locked away by strong attachment to clay minerals and iron oxides.

Soil organic matter fractions that cycle most rapidly are those most sensitive to the quantity and quality of plant residue inputs, and by contrast fractions that cycle very slowly are relatively insensitive. This means that if soil organic matter outputs are not balanced by inputs, it will be the microbial fraction that experiences the imbalance first because it cycles most rapidly. Reducing the proportion of the microbial fraction in the soil organic matter carries the risk that the soil mineralization rate will be reduced and the nutrient supply will become limited.

5.5 Soil resistance and resilience is maintained with adequate soil organic matter

Resistance = ability of soil or ecosystem to withstand degradation
Resilience = ability of soil or ecosystem to recover from some impact

Under natural and managed conditions, soils, along with other parts of the ecosystem, receive impacts which may affect their stability. The ecological concepts of resistance and resilience help us understand the consequences of these impacts.

These concepts may be understood using the analogy of a mountain biker (Figure 5.5), where the biker represents the plant biomass and the bicycle represents the soil. Should the biker be subjected to some impact, for example a strong gust of wind, then if he has strong resistance he may perhaps wobble but will be able to carry on. Low resistance, however, would cause him to fall off. If he falls and is unable to carry on, then he will lack resilience, but if he is able to pick himself up and proceed he is showing resilience. His performance after the fall would be a measure of the amount of resilience. We want the biker to enjoy good stability due to good resistance, or rapid and complete resilience.

Soil organic matter has a role in increasing the resistance and resilience of ecosystems and so ensuring their stability.

Examples:

1. Where the quantity and quality of soil organic matter, and the climate, favour rapid mineralization rates, the recovery of vegetation following the impact of heavy grazing or burning is likely to be relatively good. The plant community's resilience is maintained.
2. Because soil organic matter stores moisture, through its positive effect on soil structure, plant communities will have greater resistance to the impact of drought.
3. The concepts of resistance and resilience apply to soil properties as well as plant communities or whole ecosystems. Soil structure, for example, is generally more resistant to compaction when soil organic matter levels are high. When soils are compacted by some agent such as animal treading, they will be more resilient if soil organic matter content and quality is adequate.

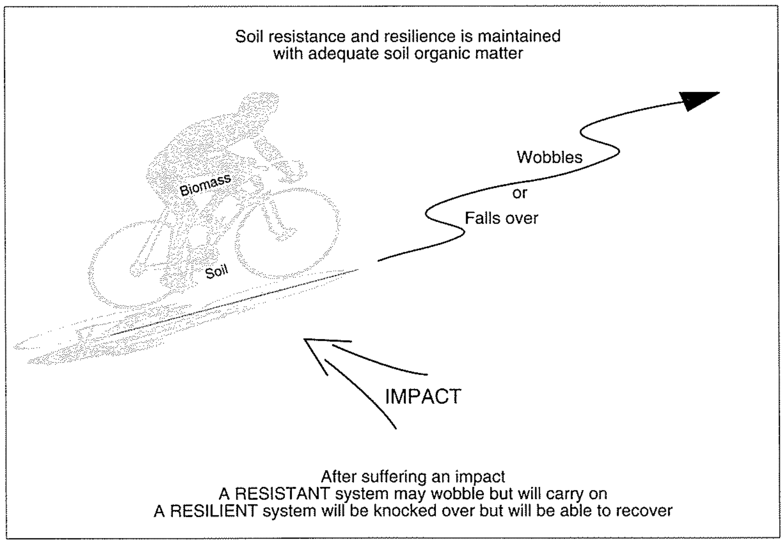


Figure 5.5
Any impact on the soil will have an effect. The soil may resist the impact and remain stable or it may decline but show a capacity to recover, that is, it shows resilience. Ideally the soil should have high resistance to change. In the mountain biker analogy our desire is that he should enjoy good stability due to good resistance, or good or complete resilience. Good soil organic matter levels are likely to maintain adequate soil resistance and resilience.

5.6 Soil organic matter is a reservoir of nutrients and acidity

Soil organic matter contains and absorbs both anions and cations. Anions are atoms or molecules with negative charge. Cations are atoms or molecules with positive charge.

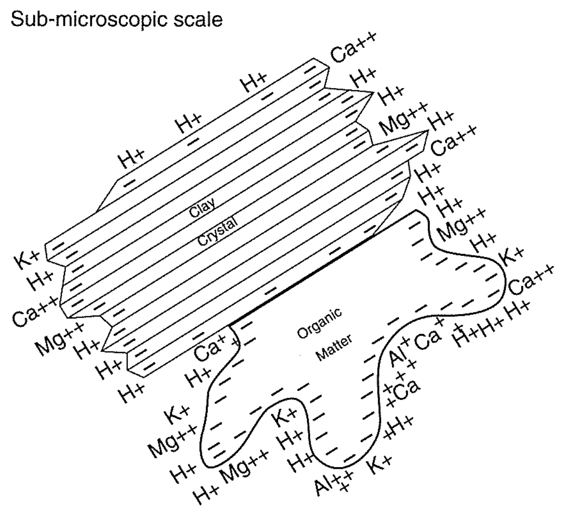
The nutrients nitrogen (N), sulphur (S) and phosphorus (P) are part of the structure of soil organic matter. Because they are tightly bound to the carbon and oxygen atoms they are said to be in "organic forms" and as such they are not available for plant uptake. They are released into mineral forms as anions (mainly nitrate NO_3^-, sulphate SO_4^{2-} and phosphate $H_2PO_4^-$). These mineral anions are then available for uptake by plant roots and soil organisms, or may be lost by drainage or to the atmosphere.

The nutrients calcium, magnesium, potassium and sodium occur as cations that are attached to the surfaces of soil organic matter fragments as well as to clays. They are called basic cations. Like clay minerals, soil organic matter has a dominance of negative charge on its surface (Figure 5.6a). This negative charge attracts the positively charged cations and this process may be assessed as the "cation exchange capacity" or CEC. The cation exchange capacity of the soil is a measure of the amount of negative charge on the surfaces of soil particles. Clay minerals contribute to the cation exchange capacity but in most topsoils CEC is dominated by organic matter.

The acid-forming cations, hydrogen (H^+) and aluminium (Al^{3+}), also occur in the cation exchange complex. In very weakly acid, neutral or alkaline soils the cation exchange complex is dominated by basic cations but in strongly acid soils it is dominated by hydrogen and aluminium cations.

The proportion of negatively charged sites (cation exchange capacity) that are occupied by basic cations is called the base saturation and is expressed as a percentage. As soils become more acid, the acidic cations displace the useful basic cations, and there is an increasing risk of aluminium toxicity for some plants (particularly below pH 5.5).

Cation exchange capacity, base saturation and the amount of topsoil carbon in relatively undegraded soils vary systematically with climate through the sequence from Semiarid Soils and Pallic Soils to Brown Soils (Figure 5.6b).



Soil organic matter contributes a large amount of negative electrical charge to the soil
= CATION EXCHANGE CAPACITY

The negative charges attract positive electrically charged cations - including
basic cations
mainly calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na)
acidic cations
hydrogen (H) and aluminium (Al)

The proportion of basic cations (Ca, Mg, K, Na) to acidic cations (H, Al)
= BASE SATURATION

(for example, if CEC = 15 cmol/kg%, and basic cations = 10 cmol/kg% then base saturaton = 66%)

Figure 5.6a

A sub-microscopic view of soil shows that the surfaces of clay and organic matter particles are bristling with negative charges. The *cation exchange capacity* of the soil is a measure of the amount of this negative charge. Cations are attracted to these negative charges. The proportion of basic cations (mainly calcium, magnesium, potassium and sodium) attached to the negative charge is called the *base saturation* and is expressed as a percentage. For example, if CEC = 15 cmol/kg% and base cations = 10 cmol/kg%, then base saturation = 66%.

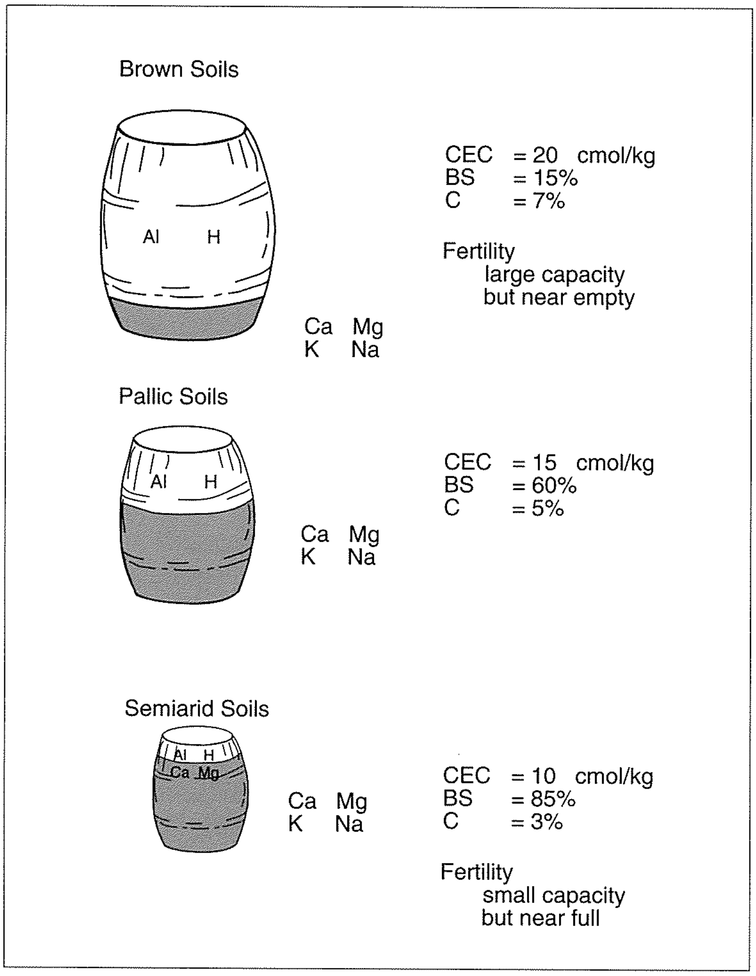


Figure 5.6b
Barrels of fertility represent the cation exchange capacity and base saturation for the sequence of Semiarid Soils to Brown Soils.

6. Loss of soil organic matter in a range of environments

6.1 Consequences of loss

The consequences of loss of soil organic matter by either reduction of inputs or erosion have an impact on the chemical, physical and biological health of the soil (Figure 6.1a).

Some consequences are more serious for certain soils. For example, structural stability is more seriously affected by loss of soil organic matter in Pallic and Semiarid Soils than in Brown Soils. Structural stability is generally greater in Brown Soils (particularly Allophanic Brown Soils) than Pallic Soils and Semiarid Soils (Figure 6.1b page 26). Brown Soils have more iron and aluminium oxides which, together with humus that is tightly bound to the oxides, stabilise structure and resist compaction. Pallic Soils, and particularly Semiarid Soils, have very low contents of iron and aluminium oxides and their stability relies on adequate levels of soil organic matter. Loss of soil organic matter promotes instability and lowers resistance to compaction.

Increased acidity caused by fertilizers or removal of herbage is more likely in soils poor in soil organic matter. The rate at which soil pH responds to addition of acids, or to neutralisation, is called the buffering capacity. The capacity of a soil to buffer increases with organic matter content. Semiarid and Pallic Soils are likely to have lower buffering capacities than Brown Soils and therefore be more susceptible to acidification. Loss of soil organic matter will increase this susceptibility.

The loss of soil organic matter by erosion will have a greater effect on the content of basic cations in Brown Soils than Pallic Soils or Semiarid Soils. The subsurface horizons of Brown Soils (particularly the Allophanic Brown Soils and Acid Brown Soils) have very low contents of basic cations (base saturation ranges from 40% to 1%) and much of the basic cation fertility of these soils is concentrated in the soil organic matter. In the Pallic Soils and Semiarid Soils, however, subsurface horizons are relatively fertile, having reasonably high cation exchange capacities with reserves of basic cations (Figure 6.1c page 27).

Soil organic matter holds reserves of phosphorus, sulphur and nitrogen. These reserves are lost in all soils in proportion to the loss in organic matter.

Consequences of the loss of soil organic matter

1. **On chemical health**
   - Reduced reserves of nitrogen, phosphorus and sulphur
   - Reduced reserves of basic cations - calcium, magnesium, potassium and sodium
   - Increased susceptibility to chemical influences including acidification, and cation and anion leaching
2. **On physical health**
   - Reduced structural stability
   - Reduced capacity to absorb, and store water
   - Reduced insulation from extreme temperatures
3. **On biological health**
   - Reduction in soil animals
   - Reduction in microbial population
   - Reduced soil mixing and rate of nutrient cycling including mineralization

Figure 6.1a.
Consequences of the loss of soil organic matter on soil condition.

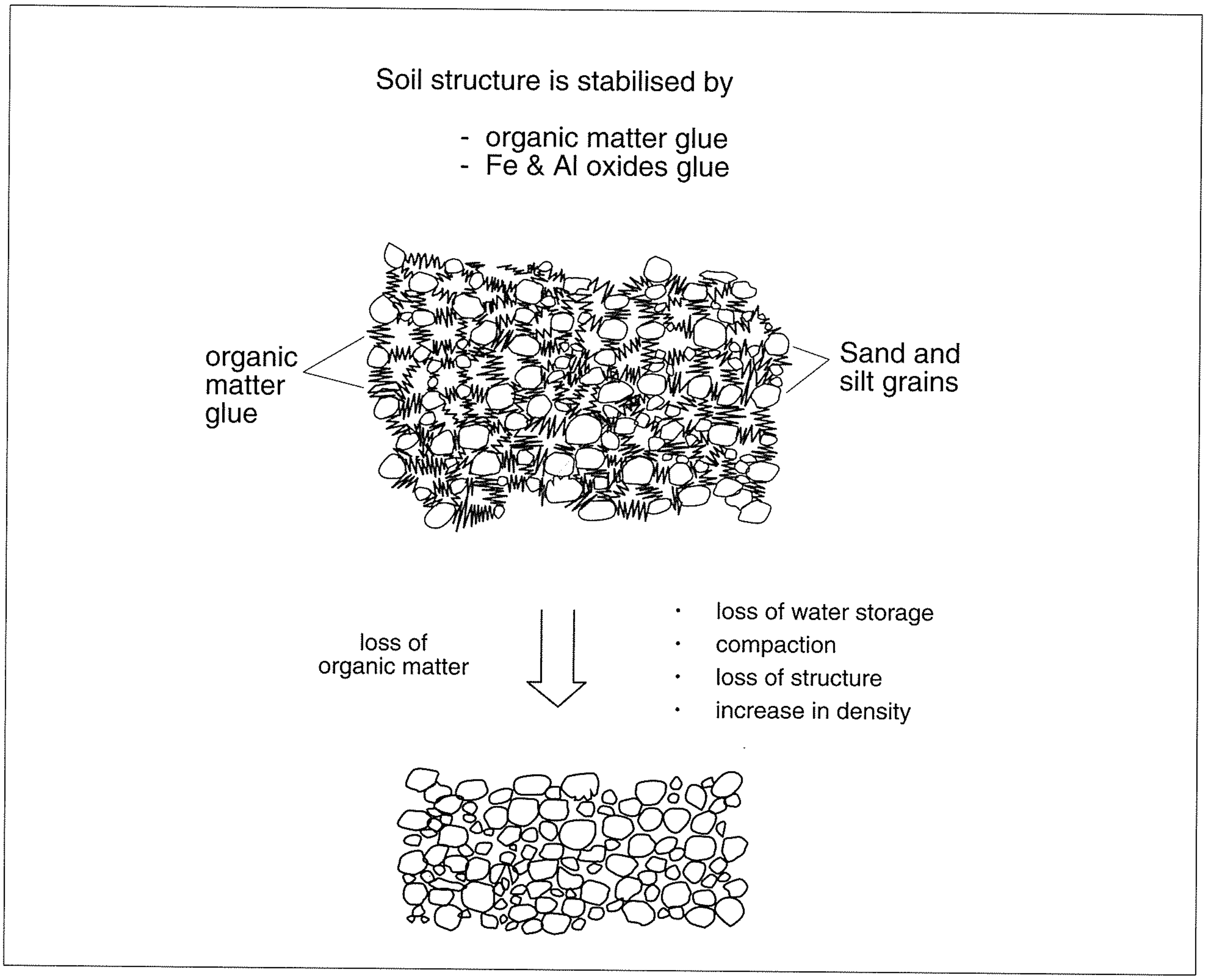


Figure 6.1b

Soil structure is stabilised by organic matter and iron and aluminium oxides. Loss of organic matter, particularly in Semiarid Soils and Pallic Soils that have low iron and aluminium oxides, will destabilise structure, with possible loss of water storage, and increase in density (compaction). Brown Soils, particularly the Allophanic Brown Soils, have greater inherent stability.

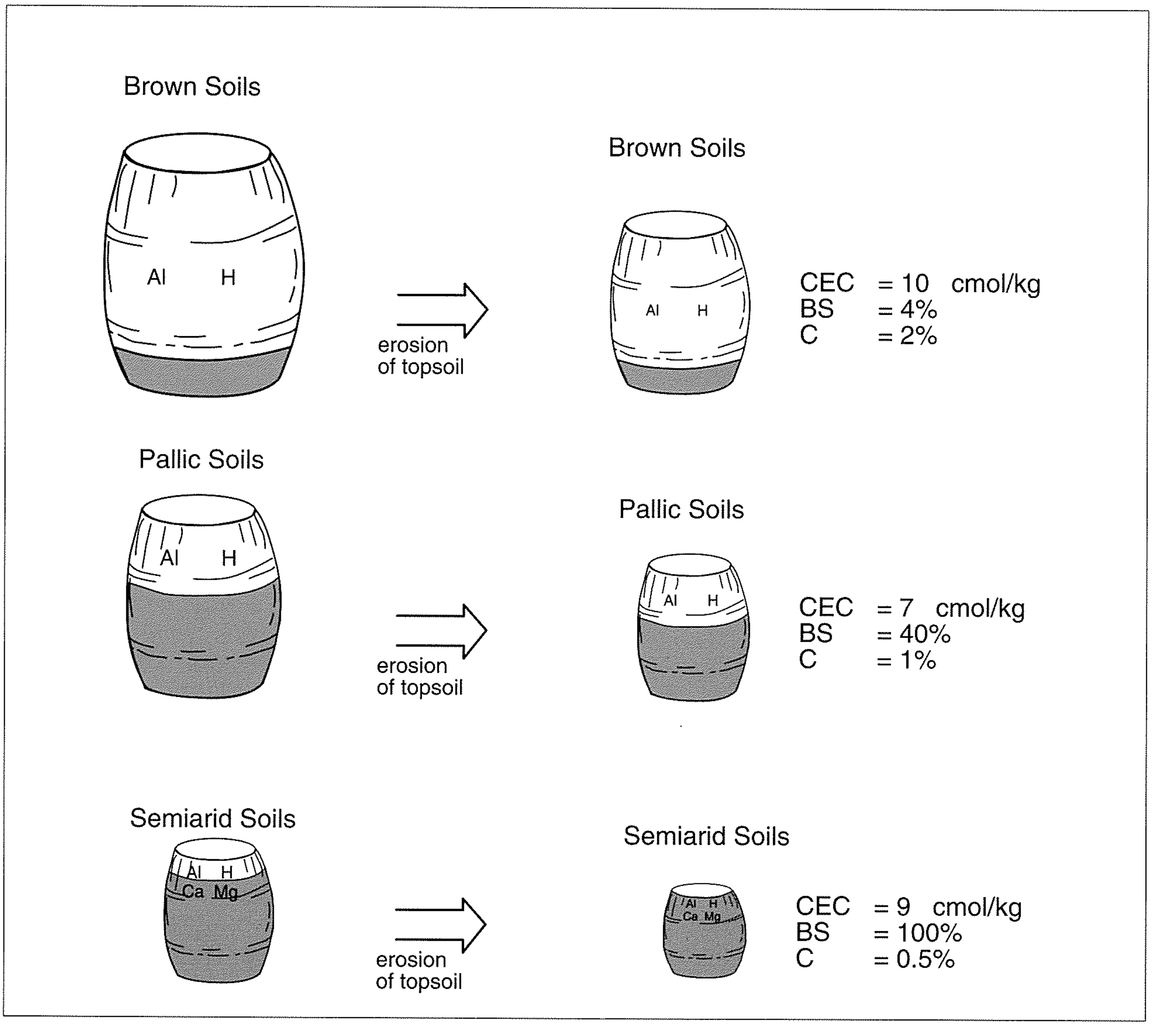


Figure 6.1c

With loss of organic matter by erosion of topsoils, the fertility barrels shown in Figure 5.6b have shrunk. The base saturation has reduced in the Brown Soils and Pallic Soils but has increased in the Semiarid Soils (because subsoils are rich in bases). For all soils, reserves of phosphorus, sulphur and nitrogen held in soil organic matter are lost in proportion to the loss of organic matter.

6.2 Approaches to monitoring soil carbon

There are four lines of evidence that may indicate change in carbon levels in the high country over time.

(a) *Monitoring change by repeated sampling over time.* Total carbon levels change very slowly so that monitoring must occur over a long time (decades). Microbial carbon changes more rapidly and may provide an early indication of the direction and rates of change (years).

(b) *Comparing apparently degraded and non-degraded sites on similar soils.* Finding ready made benchmark areas that have been little modified can be difficult, particularly in the lower, more intensively grazed high country. However, exclosure plots that exclude sheep and rabbits need not be large, and can yield valuable results. Where there are no benchmarks, good results can be obtained by measuring carbon in pairs of sites of contrasting condition which may be related to management. The data from many such pairs can then be analysed to derive a soil condition gradient, similar to the plant condition gradients determined in a similar procedure[6].

(c) *Application of carbon cycling models to predict rates of change.* Carbon cycling models simulate the cycling of carbon through the carbon fractions (see section 5.4) and may be used to estimate organic carbon input rates and soil carbon steady state levels and rates of change. The carbon cycling models "Rothamsted" and "CENTURY" are both being tested in New Zealand.

(d) *Using ratios to indicate trends.*High microbial carbon to total carbon is good because it indicates a soil with an active organic cycle. The amount of carbon in the microbial fraction of the soil may be compared with total carbon to indicate the existence of a degradation or recovery trend. A degrading soil will preferentially lose the microbial carbon fraction (see Section 5.4), and the ratio of microbial carbon to total carbon will therefore be low. In recovery, however, the microbial carbon fraction will increase more rapidly than other fractions and the ratio of microbial carbon to total carbon will therefore be high[7].

6.3 Appropriate indicators for monitoring and their interpretation

Soil organic matter quantity

As discussed in section 2.4 carbon content (reported as either "organic carbon" or "total carbon"), is the best means of measuring soil organic matter quantity.

Indicator:

Organic carbon (%C)

Interpretation:

Evidence suggests that total carbon of less than about 2.5% in the topsoil indicates that the soil is in poor condition. Below this level, soil management modification to raise total soil carbon content should be considered. Ideally management decisions would be made on the basis of a trend over time. A low carbon level with a decreasing trend would require changed management but an increasing trend would indicate appropriate soil management. However, historical records of organic carbon are rare, and rates of change are slow.

In the Semiarid Soils, soil structure and associated soil properties (water infiltration rate, compaction, soil surface crusting, penetration resistance and water repellency) have poorer quality below about 2.5% organic carbon. A similar threshold is indicated for the Pallic Soils and its likely application to a wide range of soils and environments is suggested by the independent observation that 2.5% carbon is a significant soil quality limit in Recent Soils in the

6 *Gibson, R.S.; Allen, W.J.; Bosch, O.J.H. 1995. Condition assessment concepts and their role in facilitating sustainable range management. Annals of arid zone. 34:179-189.*

7 *Sparling, G.P.; Shepherd, T.G.; Kettles H.A. 1992: Changes in soil organic C, microbial C and aggregate stability under continous maize and cereal cropping, and after restoration to pasture in soil from the Manawatu region, New Zealand. Soil and tillage 24: 225-241.*

Manawatu (Shepherd 1990). Some Recent Soils, under good management and vegetation cover may, however, have naturally low carbon contents because they are in the slow natural process of accumulating carbon from very low initial levels. This may be the case for Fluvial Recent Soils adjacent to rivers. Figure 3.1e shows that carbon levels below 2.5% are predominant in the Semiarid Soils and common in the Pallic Soils.

The adequacy of soil organic matter levels can be judged in the field by examining the topsoil structure. An index is being developed in which topsoil structure condition is used as a first case assessment of organic matter levels. Appropriate soil structure indicates that soil organic matter levels are adequate, poor soil structure indicates that levels may be low and there is need for further investigation. The Farmers Resource Monitoring Kit provides information on monitoring strategies[8].

In some situations, total organic carbon may be present in adequate concentrations, but the microbial carbon fraction may be depleted. Critical levels of microbial carbon have not yet been identified.

Soil organic matter quality

Indicators of soil organic matter quality are not fully developed. Because evaluation of soil condition must consider chemical, physical and biological properties, more than one indicator will be needed to provide a reliable picture of soil organic matter quality. A short list of possible indicators includes:

- microbial population and activity
- acidity (as measured by pH)
- major nutrients (as measured by fertiliser recommendation quick tests)
- total nitrogen
- worm count or nematode count.

Measurements of the microbial population and its activity can be excellent indicators of soil organic matter quality and have relevance to chemical and physical as well as biological health. The measurements are expensive and require controlled handling of samples. Current research will identify the most effective indicators.

Measurement of pH is a rapid and cheap method of expressing acidity and general level of soil fertility. Because the cation exchange capacity of topsoils is dominated by soil organic matter, pH provides a measure of cations (calcium, magnesium, potassium and sodium) on the cation exchange complex.

Indicator:
pH

Interpretation:

pH 5.5 - 7.0	adequate cations
pH 4.8 - 5.4	nutrients limited, possible aluminium toxicity
pH less than 4.8	aluminium toxicity likely to be strong

The presence of aluminium, toxic to many introduced plants, is a major reason why strong acidity is undesirable in soils. Soil tests are under development (K. Powell, University of Canterbury) that will directly measure the content of aluminium in forms that are toxic to plants.

The relationship between carbon and total nitrogen provides a crude measure of the amount of decomposition of soil organic matter. Well decomposed humus has a ratio of carbon to nitrogen (C/N) between 8 to 16 depending on climate. In soils in which microbial activity has been limited, plant fragments are poorly decomposed and C/N ratios are greater than 16, and as high as 40 in some acid peat soils.

High worm numbers are associated with enhanced rates of soil organic matter cycling and good soil nutritional and physical health. Not enough is known about the worm species present and their populations in high country soils to be able to set monitoring guidelines. It is possible that other soil animals, for example some species of nematodes, will also provide useful indicators.

8 *Aspinall, J. ed. 1994. Farmer resource monitoring kit. High Country Committee Federated Farmers, Timaru.*

7. Management for soil organic matter maintenance or recovery

The rate at which soil organic matter levels will recover under natural conditions depends greatly upon the productivity and management of the vegetation.

The cycling of organic matter from plants to the soil occurs by (see sections 5.1 and 5.2)

- root growth
- litter fall and incorporation into the surface soil
- dung and urine return from grazing animals.

This material is transformed into soil organic matter by the action of living organisms in the soil including worms, bacteria and fungi (see sections 5.1 and 5.4).

Natural rates of recovery can be very slow (see section 5.3), but may be accelerated by increasing plant productivity and conditions that will favour the activity of living organisms in the soil. Vegetation productivity and incorporation of organic matter into soil is encouraged by the following practices.

Fertilisation

If plant production is limited by soil fertility, then addition of fertilisers will increase plant production and cycling of organic matter to the soil. Figure 7.1 shows the effect of oversowing and topdressing on soil organic carbon and nitrogen. With the development of highly productive pastures, however, there is a risk that excess nitrate will be mineralised and released into the environment.

Encouraging good plant cover

Good plant cover increases the number of plants that will cycle carbon to the soil, keeps the soil cooler in summer, and warmer in winter, and maintains the decomposing activity of soil organisms.

These effects of increased plant cover and plant production may be reduced by fertility transfers (see section 5.2). Organic matter may easily be transferred from well vegetated areas and concentrated elsewhere.

Encouraging litter accumulation

Litter is dead plant material that has accumulated at the soil surface. It forms a mulch which is a porous spongy layer that retains moisture and insulates the soils against the extremes of winter and summer temperatures. When litter becomes thick, however, transfer of nutrients to the mineral soil may be impeded.

Irrigation

Where plant production is limited by soil water, irrigation will increase plant production and cycling of organic matter to the soil.

Grazing management

Grazing pressure needs to be matched to the productive capacity of the vegetation. Good grazing management will maintain plant productivity at levels that will maintain soil organic matter. This will require adequate management of soil fertility. Figures 7.2a and b show a case study in which organic carbon increased after nine years of nil grazing. Greater increases occurred where nil grazing was combined with oversowing and topdressing.

Direct incorporation of organic matter

Direct incorporation of organic matter is more relevant to cropping land than pastoral land. Stubble remaining after harvesting and crops especially grown for the purpose may be ploughed into the soil. Manure, usually the waste product of intensive animal farming, may be spread or irrigated onto the soil surface.

Minimum-tillage

Tillage has the effect of breaking open soil aggregates and exposing organic matter trapped in very fine pores to decomposition. Mineralisation is increased and soil organic matter levels may decrease. Minimum tillage helps to maintain higher soil organic matter levels in cropped soils.

The significance of non-palatable plants

Non-palatable plants such as stonecrop (*Sedum acre*), thyme (*Thymus vulgaris*), briar (*Rosa rubiginosa*) and plants which stock find hard to eat, such as hawkweed (*Hieracium* sp.), may possibly be quite efficient at cycling organic matter into the soil. Carbon is known to increase under hawkweed. In some places where the soil is in particularly poor condition, it may be cost effective to allow unpalatable weeds to bring about soil recovery.

The soils most at risk

The soils most at risk from loss of soil organic matter are generally those on sunny aspects, and in particular, upper slopes. These soils are relatively shallow, exposed to drying north-west winds, preferentially grazed and most susceptible to erosion (see Figures 3.2b and 5.2).

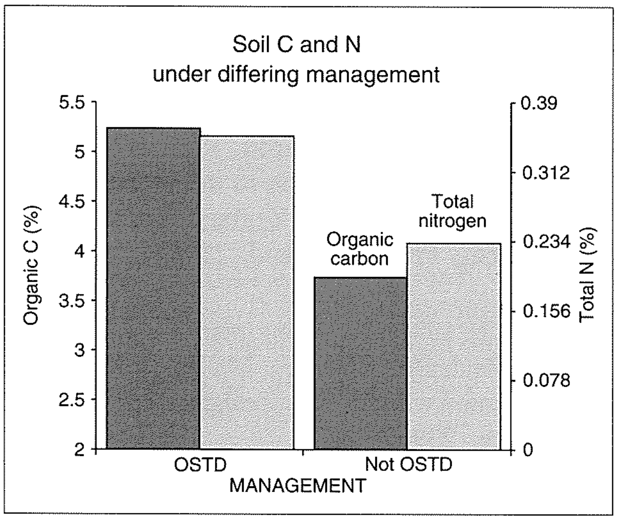
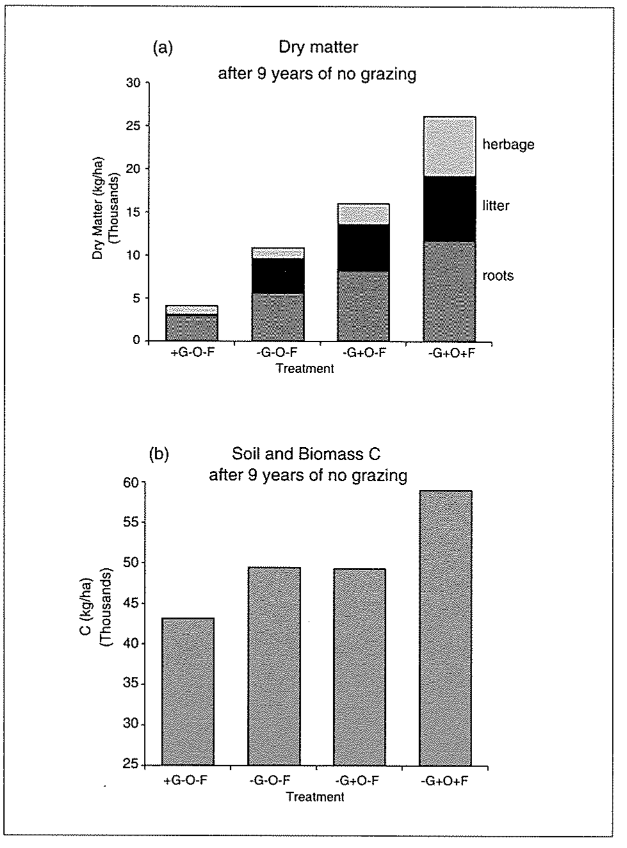


Figure 7.1

Oversowing and topdressing (OSTD) increases organic carbon and total nitrogen in soils. In this example, mean organic carbon and total nitrogen values in 0-7.5 cm soils from 10 sites oversown and topdressed with about 1 ton of S-superphosphate over 15 years are compared to mean values on a neighbouring block with identical Brown Soils that have not been oversown and topdressed. Absolute total carbon values are 1.5% higher (41% increase), and total nitrogen values 0.12% higher (52% increase), on the oversown and topdressed block. Both differences are statistically significant.



Key:

+G = grazed with about 0.6 ewe/ha, -G = not grazed
+O = oversown with legumes, -O = not oversown
+F= fertilised with S-superphosphate, -F = not fertilised

Figure 7.2a

Stopping grazing for nine years not only increases the amount of standing herbage (as expected), but also doubles the amount of litter and roots. Oversowing and topdressing, without grazing, results in a further doubling of the amount of litter. All measurements made in summer 1994.

Figure 7.2b

Stopping grazing also raises the level of soil carbon at 0-25 cm depth. The effect is most pronounced under the "soil conservation option" of stopping grazing together with oversowing and topdressing (-G+O+F). The "soil conservation option" raises organic carbon to levels above the 2.5% C "critical level". Similar results were found for total nitrogen.

8. Acknowledgements

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