SURVEY OF NEW ZEALAND SOIL ORDERS

Allan Hewitt
Landcare Research, PO Box 40, Lincoln 7640, New Zealand

ABSTRACT: The diversity of soils in New Zealand is demonstrated by the range of soil orders in the New Zealand soil classification system. These are briefly described, and depicted in a national 1:3 000 000 scale soil map. Two types of soil properties are contrasted. Inherent soil properties define the substance of the soil body that is relatively unchanging over human timescale. This is the primary focus for national soil resource surveys. Dynamic soil properties indicate the effects on the soil of land use pressures and are measured to assess the soil quality (also known as soil health). Both the inherent and dynamic soil properties are important for the evaluation of soil natural capital. Data sources in New Zealand for soil properties are described

Key words: soil natural capital, soil classification, soil properties, soil quality.

INTRODUCTION TO NEW ZEALAND SOILS

The natural capital context of New Zealand soils

Soil natural capital and soil services provide a way of viewing New Zealand soils that highlight the connections between our soils and how they support the ecosystem services that sustain us. Dominati and colleagues (Dominati et al. 2010; Dominati 2011) provided a framework that shows the nature of these connections. In essence, soil natural capital is comprised of a set of soil stocks. The concept of soil carbon stocks is familiar, but many other stocks make up the substance of the soil and support its functioning. Soil services are the flows of material, or energy, released by soil processes acting on the stocks that ultimately provide the benefits we enjoy from soils. This chapter assumes that the soil profile, or pedon, is a practical minimum unit of soil natural capital.

What would an ideal soil look like?

If we could breed soils what would a champion soil look like? This was a question posed by Eddie Cutler of Lincoln University in the 1960s. His answer was conditioned by the prevailing productive pastoral agricultural landscape in which he worked. His ideal soil would have crumb structure (like breadcrumbs), a fine sandy loam texture, and be well drained. Forty years later, however, we would have to answer by saying ‘it depends’. Different plants and land uses require quite different kinds of soil. For example, a champion soil to support pasture for dairy grazing requires a high capacity to store water. Water stress that would reduce pasture growth must be avoided. In the same locality a soil to produce medal-winning wines would need the opposite capacity, as low water storage capacity is needed to induce the drought stress required to cause the grapes to make the sugars that will turn to alcohol.

Of course we cannot breed soils but we can modify them in ways that can persist for long periods of time. Modification examples include drainage to remove excess water and liming to make soils less acid and more hospitable to the plants we grow as food for animals and humans. A more drastic example is deep ripping or ‘flipping’, where the entire soil profile is inverted to break up impermeable layers to improve drainage. How long these changes will endure is unknown but some may persist for centuries.

Critical soil natural capital stocks

Although land uses require a variety of soil conditions, some soil properties prove to be important for most land uses. These are the key soil properties that need to be measured in our soil resource surveys and which define our critical soil stocks. In practice, soil surveyors collect data on a minimum dataset of fundamental soil properties that can be rapidly assessed in the field, such as texture, colour, soil strength, structure, soil horizons, and depth. These are then used to model more difficult properties such as profile available water capacity, bulk density, macroporosity, and permeability. These, and other derived properties are the common inputs required by land management models.

The soil properties, necessary for modelling the soil processes that replicate the operation of 10 important physical soil services (or soil functions), were reviewed to determine the critical set of soil natural capital stocks. Twelve critical soil stocks were identified. Properties of soil horizons were: permeability (hydraulic conductivity), phosphate retention, carbon content, macroporosity, plastic limit, bulk density, and functional horizon. Properties of the soil profile were: potential rooting depth, annual water regime (deficit period, and water surplus), profile available water capacity, drainage class, and New Zealand soil classification class. These properties are defined by Milne et al. (1995), Hewitt (2010), Webb and Lilburne (2011). Another survey of critical soil stocks, expressed more in terms of the fundamental properties, was made by Dominati (2011).

The operation of soil services depends on the quality of the underpinning soil natural capital stocks. It is possible to estimate the efficacy of a soil service at a site by examining the soil properties and knowing the response of the service to the property levels. A simple example is the water storage service. It is dependent on the soil profile available water capacity, derived in turn from the fundamental properties of texture, stones, and effective rooting depth. This type of dependency has been utilised by Hewitt et al. (2012) to develop the stock adequacy method for quantifying soil natural capital.

NEW ZEALAND SOIL ORDERS

This section briefly reviews New Zealand soil classification (NZSC) orders (Hewitt 2010). The order level of the soil classification is successively subdivided into groups, subgroups, soil families, and siblings. For details refer to Hewitt (2010), Webb and Lilburne (2011), and Molloy (1993), and Hewitt (2007).

The 15 New Zealand soil orders are briefly outlined in the following. A useful way of understanding the differences between the soil orders is to arrange them according to the dominant factors that have influenced their character, by the dominance of the following factors in their formation: age, climate, wetness, and rock type (Table 1).

TABLE 1 Organisation of New Zealand Soil Classification (NZSC) soil orders. This is not a formal part of the NZSC but merely a means to help understand the relationships between the soil orders. The NZSC key to orders (Hewitt 2010) should be used to classify specific soils to soil orders.

Young soils		Raw Soils Recent Soils Anthropic Soils
Mature soils *Soils that have well developed topsoil and subsoil horizons*	***Climate*** *Soils formed in quartz rich materials that show the effects of climate*	Semiarid Soils Pallic Soils Brown Soils Podzols
	Wetness *Soils with prolonged high water tables*	Gley Soils Organic Soils
	Rock *Soil parent materials formed from rocks that dominate the soil character, e.g. limestone, basalt, pumice and volcanic ash*	Melanic Soils Pumice Soils Allophanic Soils
Old soils *On land surfaces with parent materials that have attributes of advanced weathering*		Ultic Soils Granular Soils Oxidic Soils

Young soil orders: Raw Soils, Recent Soils, and Anthropic Soils

These weakly developed soils occur on young parts of the landscape in places where erosion or deposition of sediments is active; on steep slopes and rocky outcrops, sand dunes of the coast, flood plains of rivers, ash and cinders close to active volcanoes, tidal estuaries, and cities where the soils are disturbed. Examples of Raw Soils, Recent Soils, and Anthropic Soils are shown in Figures 1, 2 and 3.

Raw Soils — Raw Soils are infant soils that will probably never grow old because they occur in places where erosion or sediment deposition is active. The topsoil is missing or it is very thin. These soils are not farmed, as plant growth is limited by frequent disturbance and fertility. They are scattered throughout New Zealand, particularly in association with high mountains (alpine rock areas and active screes), braided rivers, beaches and tidal estuaries. In area they cover 3% of New Zealand.

Raw Soils have no B-horizon, and the topsoil is either absent or less than 5 cm thick. Fertility is limited by lack of sufficient organic matter to provide nitrogen and other nutrients. Vegetation cover is sparse and often consists of colonising species including ephemeral herbaceous plants, mosses, or lichens.

Recent Soils — Recent Soils are weakly developed, and show limited signs of soil-forming processes, but a distinct topsoil indicates more advanced development than Raw Soils. A B-horizon is either absent or only weakly expressed.

Recent Soils are in land where erosion or sediment deposition levels are low enough to allow time to form well-developed topsoils. Soil formation is either absent or only weakly expressed in the subsoil. These soils are usually fertile and are deep rooting unless rock or dense clay is present. They occur throughout New Zealand on young land surfaces, including alluvial floodplains, sand dunes, unstable steep slopes, and slopes mantled by young volcanic ash. Their age varies depending on the environment and soil materials, but most are less than 1000–2000 years old. They cover 6% of New Zealand.

The soils have variable soil texture, with common stratification of contrasting materials, and frequently very high spatial variability. Unless rock or dense clay is present at shallow depths, they are generally deep rooting and have good water storage capacity. In contrast with Raw soils they are naturally fertile. Many of New Zealand's most versatile soils are Recent Soils. A continuous cover of vascular plants is normally well established.

Anthropic Soils — Anthropic Soils are constructed by, or result from drastic disturbance by the action of people. They include soil materials formed by stripping of the natural soil, deposition of refuse or spoil, or by severe soil mixing. The original character of the soil and the normal soil properties may be considerably altered. Anthropic Soils are made by people: by deposition of rubbish in landfills; by stripping away the natural soil; or by constructing earthworks. Most extensive in urban areas they are also common in mined land.

In the past 20 years substantial areas have been formed in the Westland region through modifications of very wet soils called 'humping and hollowing' and 'flipping' to improve soil drainage. The other extensive area of Anthropic Soils was formed by gold dredging in Central Otago and Westland. Known Anthropic Soils cover <1% of New Zealand, but the areas formed by modification of very wet soils in Westland have not yet been surveyed.

The relationships between Anthropic soils and landforms do not have the expected relationships of natural soils. Their properties depend on both the nature of the manufactured or natural materials and the nature of the soil manipulation. Land surfaces are artificial and drainage has often been changed from the original state.

Climate-dominated soil orders: Semiarid Soils, Pallic Soils, Brown Soils, and Podzols

Collectively, the Semiarid Soils, Pallic Soils, Brown Soils,

FIGURE 1 Raw Soils profile formed in dune sand.

FIGURE 2 Recent Soils profile formed in deep loamy alluvium.

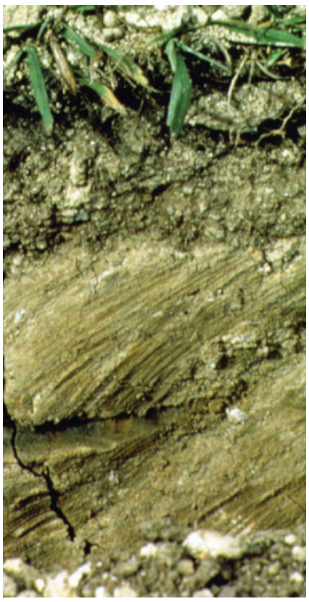

FIGURE 3 Anthropic Soils profile formed on a sports field where soil material has been transported on the site and compacted by heavy machinery.

FIGURE 4 Semiarid Soils profile formed in loess overlying alluvium. The brown layer is a horizon of clay accumulation which may restrict water penetration.

FIGURE 5 Pallic Soils profile formed in loess. A hard fragipan in the middle severely restricts root and water penetration.

FIGURE 6 Brown Soils profile showing the contrasting colour and structure with increased rainfall compared to the Pallic Soil in Figure 5.

FIGURE 7 Podzols soil profile showing strong differentiation of soil horizons.

and Podzol orders extend over 73% of New Zealand. They differ in their climate and show the effect of rainfall on soil development, particularly on leaching. The first three in this sequence may form under a range of vegetation types, but Podzols are restricted mainly to native forests or areas where there have been native forests. They occur predominantly on quartz-rich parent materials, commonly from greywacke, pumice, schist and granite. Examples of Semiarid Soils, Pallic Soils, Brown Soils, and Podzols are shown in Figures 4, 5, 6 and 7.

Semiarid Soils — Semiarid Soils are dry for most of the growing season. They are located in the inland basins of Otago and Canterbury where annual rainfall ranges from 350 to 500 mm. There is too little rain to wash out the sodium, calcium and other elements released from the slow weathering of the parent material. Consequently, lime-rich and in some places saline deposits accumulate in the subsoil. Irrigation flushes out the salts, transporting them into low parts of the landscape. Nutrient levels are relatively high, but the soils must be irrigated to produce a crop. The Semiarid Soils cover 1% of New Zealand.

The soils have high slaking and dispersion potential, and moderate to high bulk densities. Soil structure is usually weakly developed and the soils are erodible. Organic matter contents are very low and consequently cation exchange capacity is low. Weathering is weak and therefore phosphate retention and iron and aluminium oxide contents are also very low. Chemically the soils are weakly buffered, meaning they can be sensitive to management changes. Biological activity is low in their natural state because of droughtiness and low organic matter contents. The soils are productive under irrigation.

Pallic Soils — Pallic Soils have pale-coloured subsoils, due to low contents of iron oxides. Subsoils frequently have weak structure and high density. Pallic Soils are dry in summer, but wet in winter, with rainfall ranging from 500 to 1000 mm in the South Island, and less than 800 mm in the North Island. They are called Pallic because of the pale yellow straw colour of the subsoils. Many Pallic Soils have restricted use (predominantly sheep grazing) because of the high subsoil density that prevents roots from penetrating deeply and accessing deeper moisture. Drainage of excess water in winter is also limited by the density, and causes topsoils to be very wet in winter or spring. Some younger Pallic Soils, though, are less dense and capable of a wide range of uses. Pallic Soils cover 12% of New Zealand.

Iron and aluminium oxides, along with organic matter, have a stabilising influence on soil porosity and structure. In Pallic Soils low contents of these stabilising materials, particularly in subsoils, mean that the soils are susceptible to erosion, especially to slaking and dispersion. A feature of many of the soils is the strong worm mixing common at the boundary of the topsoil and subsoil, because of worms burrowing deep to escape summer drought.

Brown Soils — Brown Soils have a brown or yellow-brown subsoil below a dark grey-brown topsoil. They extend over the mountainous and hilly backbone of New Zealand and onto the moist lowlands where summer droughts are uncommon and soils remain moist throughout the year (except in some sandy or very stony soils that may be droughty). Rainfall is usually more than 800 mm (south) or 1000 mm (north). The relatively wet climate has also caused leaching of nutrients – washed into drainage waters and eventually into streams and rivers – so the soils are acid in their natural state with limited natural fertility. When fertilised, Brown Soils make good sheep, beef and dairy land, for example on the Southland Plains. Brown Soils are our most extensive soils and cover 43% of New Zealand.

Brown Soils, in contrast with Semiarid Soils and Pallic Soils, are more highly leached and weathered as expressed in lower natural fertility, greater acidity and brown colours. The colours are due to dispersed complexes of iron and aluminium hydrous oxides and organic matter. These are the materials that stabilise soil structure and porosity. Clay minerals are dominantly mica/illite and vermiculite. and allophane in Allophanic Brown Soils. The soils contain active populations of soil organisms. Although rainfall is mainly greater than for Pallic Soils, Brown Soils do occur in lower rainfall areas in very stony and sandy materials. In these low water holding capacity soils leaching under low rainfall

FIGURE 8 Gley Soils with grey and rust mottled colours formed in a wet hollow between sand dunes.

FIGURE 9 Organic Soils formed in decomposing organic matter.

may be sufficient for Brown Soil formation.

Podzols — The impressive contrast in horizons (Figure 7) typical of Podzols displays the potent effect that particular tree species, for example kauri (*Agathis australis*), can have on soil formation. Beneath the topsoil a bleached, white horizon shows the colour of white quartz grains that have been stripped of brown oxide or dark organic matter by acid chelates produced by acid-leaching tree species. These mobilised chelates are deposited and transformed into complex organic-rich material in dark-coloured horizons, along with amorphous mineral material in brown and reddish horizons. Sometimes these accumulation horizons become cemented to become humus pans or iron pans. Podzol Soils occur in areas of high rainfall and are usually associated with forest trees with an acid litter. The soils occur mainly in materials from silica-rich rocks. Podzols are moist throughout the year with annual rainfall more than about 1300 mm. They cover 13% of New Zealand.

Cemented or compacted subsoil horizons are common, with associated slow permeability and limited root depth. The subsurface horizons are weakly or non-structured. The soils have low natural fertility, low base saturation, and are strongly acid. Secondary oxides and other clay minerals are strongly differentiated with depth. The vegetation comprises plants that deposit a mor-forming acid litter. The name Podzol is derived from a Russian word for wood ash from the appearance of the bleached horizon.

Soils dominated by wetness: Gley Soils and Organic Soils

Wetness can strongly affect the growth and types of plants by limiting the availability of oxygen to roots. The duration and depth to wetness is indicated by accumulation of organic matter and soil colours. Peat indicates permanent wetness, dominant grey colour indicates prolonged wetness, and rust-coloured mottles in normal brown or yellow matrix indicates intermittent wetness. Large areas of Gley and Organic Soils are now drained for farming but the wetness indicators persist as evidence of the former extent of wetlands prior to European settlement. Examples of Gley Soils and Organic Soils are shown in Figures 8, and 9.

Gley Soils — Gley Soils, together with Organic Soils, represent the original extent of New Zealand wetlands, which have been greatly restricted in area by drainage. They are strongly affected by waterlogging and have been bio-chemically reduced. They have light grey subsoils, usually with reddish brown or brown mottles. The grey colours usually extend to more than 90 cm depth. Waterlogging occurs in winter and spring, and some soils remain wet all year. The soils occur throughout New Zealand in low parts of the landscape where there are high watertables, or in hill slopes where there are seepages. Large areas of Gley Soils have been artificially drained to form productive agricultural land. Drained soils are still regarded as Gley Soils if they have the required colour indicators. They cover 3% of New Zealand.

The rooting depth of Gley Soils may be limited for many plants by oxygen deprivation below the water table. This can be exacerbated by higher bulk density. Trafficability is limited when soils are wet. Drainage is necessary for most agricultural development and when drained the soils can be very productive. Organic matter content is usually high in topsoils.

Organic Soils — Organic Soils are peat soils that are located in wetlands and wet throughout the year. They have formed in the decomposed remains of wetland plants (peat) or forest litter. Peat or litter has accumulated because decomposition rates of fresh organic matter have been less then accumulation rates in wet anaerobic conditions. Organic Soils have at least 30 cm depth or more of peat compromising the partly decomposed remains of wetland plants (peat), or at least 40 cm depth of forest litter. Some mineral material may be present but the soil is dominated by organic matter. Organic Soils can be highly productive soils when drained and fertilised. However, their use is not likely to be sustainable in the long term because drainage dries out the organic matter. Decomposition rates increase markedly and the soils begin to shrink. Organic Soils serve as sponges in the landscape, and can hold up to 20 times their weight in water. Organic Soils occur in most parts of New Zealand, or under forests that produce acid litter in areas with high precipitation. They cover 1% of New Zealand.

The soils have very low bulk densities, low bearing strength, high shrinkage potential when dried, very low thermal conductivity and high total available-water capacity. Soils also have high cation exchange capacities, and in New Zealand are commonly strongly acid. Nutrient deficiencies are common. High carbon/nitrogen ratios indicate slow decomposition rates. Many soil organisms are restricted because of anaerobic conditions.

Rock-dominated soil orders: Allophanic Soils, Pumice Soils, and Melanic Soils

The character of the material in which a soil is formed depends on three factors. The *parent rock* influences the soil minerals, and chemistry of weathering products. The *parent material* influences the texture, stoniness, depth, and water characteristics. The *mode of emplacement* influences the stratification of materials, and the spatial characteristics of the soil. In the three soil orders featured here it is the parent rock that has a particularly potent effect on the nature of the soil. Examples of Allophanic Soils, Pumice Soils, and Melanic Soils are shown in Figures 10, 11, and 12.

Allophanic Soils — Allophanic Soils are dominated by allophane (and also imogolite or ferrihydrite) minerals. These minerals do not have the ordered crystalline-lattice of usual minerals. They do have short-range-order at a molecular scale but in practice they are regarded as amorphous. They can be likened to a stiff-jelly glass-like material that in bulk maintain a very porous, low-density structure with weak strength. The soils have a distinctive greasy feel when moistened and rubbed firmly

FIGURE 10 Allophanic Soils dominated by allophane minerals, and formed in volcanic ash

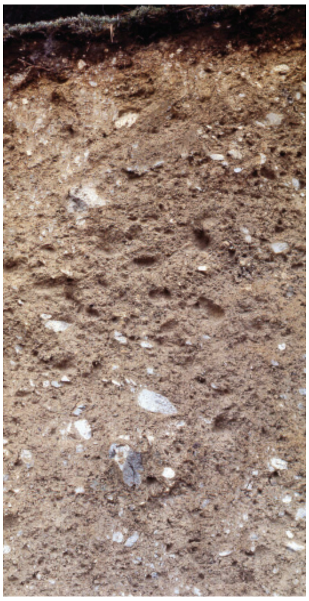

FIGURE 11 Pumice Soils formed in pumice with high content of volcanic glass.

FIGURE 12 Melanic Soils formed in limestone.

FIGURE 13 Oxidic Soils formed in strongly weathered volcanic clays with very low nutrient reserves.

FIGURE 14 Granular Soils formed in strongly weathered volcanic clays with higher cation exchange capacity than Oxidic Soils.

FIGURE 15 Ultic Soils formed in clay strongly weathered from quartz rich rocks.

between the fingers. The soil is easy to dig and samples crumble easily when crushed in the hand. The soils occur predominantly in North Island volcanic ash and in the weathering products of other volcanic rocks. Allophanic Soils may have pumice parent materials if the pumice has weathered to the extent that allophanic material that meets soil classification criteria are present. Allophane-like materials also form from the weathering products of greywacke and schist in the South Island high country, but few of these sites are recognised as Allophanic Soils because the material has insufficient thickness – such soils are recognised in the Allophanic group of the Brown Soils (i.e. Allophanic Brown Soils). The Allophanic Soils cover 6% of New Zealand.

Because the bulk density is low there is little resistance to root growth. Topsoils are stable and resist the impact of machinery or grazing animals in wet weather. They have relatively low susceptibility to erosion except on steep slopes or exposed sites. The soil has the ability to retain large amounts of phosphorus. Up to 30 tonnes/ha of phosphorus may be locked away in intensely farmed topsoils. Allophanic Soils are among our most versatile soils, where, for example in the Hamilton basin, they support a wide range of uses.

Pumice Soils — The Pumice Soils are derived from pumice ranging from 1700 to 3500 years in age. The bulk of the pumice came from the extremely large and violent eruptions from the crater now occupied by Lake Taupo. The soils are sandy or gravelly dominated by pumice, or pumice sand with a high content of sand-sized natural volcanic glass. Drainage of excess water is rapid but the soils are capable of storing large amounts of water for plants. Pumice Soils are predominantly in the central North Island, particularly in the Volcanic Plateau. They cover 7% of New Zealand.

Pumice Soils have low soil strengths, high macroporosity, and deep rooting capacity. Clay contents are low, generally less than 10%, with clay minerals dominated by allophane. Soils have low strength when disturbed, the pumice is fresh or only moderately weathered. They have low reserves of major nutrient elements and trace elements are likely to be deficient. Pumice Soils are extensively used for commercial forestry. They were found to be poor soils for raising animals until it was discovered they were deficient in trace elements such as cobalt, copper, molybdenum, boron, iodine, and selenium.

Melanic Soils — Melanic Soils are perhaps the most naturally fertile soils in New Zealand. They are derived from rocks rich in calcium (e.g. limestone) or magnesium and iron (from mafic-rich, dark-coloured volcanic rocks). Calcium and magnesium are important nutrients, and as cations they stabilise organic matter, and promote good structure. Consequently Melanic Soils are highly fertile, productive soils with organic-rich black topsoils. The name ‘Melanic’ refers to the characteristic black or very dark topsoil colours. The subsoil either contains lime or has well-developed structure and is pH neutral or only slightly acid. Melanic Soils occupy small areas scattered throughout New Zealand, in association with lime-rich rocks or dark (basic) volcanic rocks. Melanic Soils cover 1% of New Zealand.

The soil clay fraction is usually dominated by swelling (smectite) clays. This causes the soil to shrink on drying and swell on wetting. This, together with high natural soil organic matter

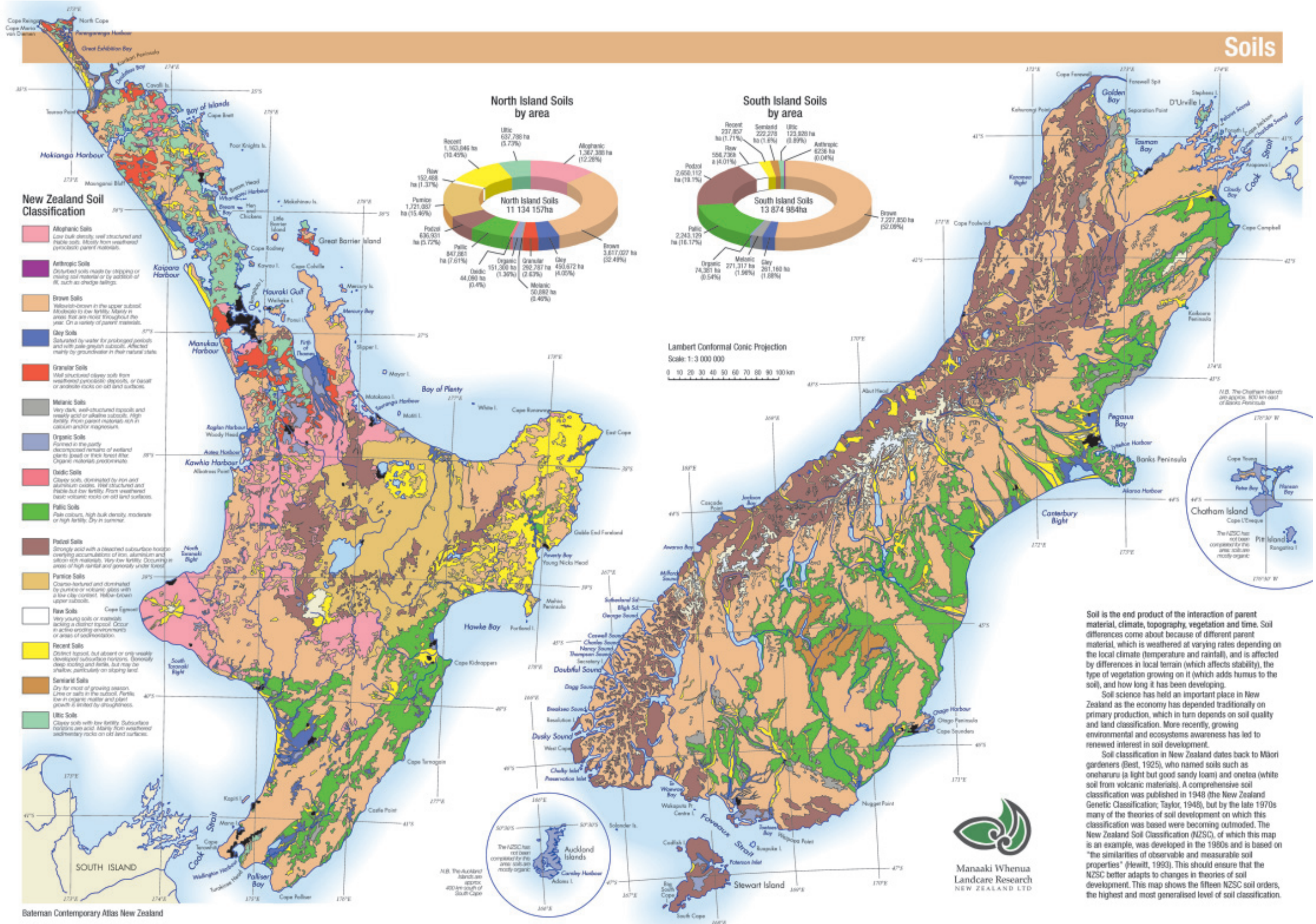

FIGURE 16 Soil map of New Zealand (permission Bateman publishers)

content, promotes well-developed and resilient structure. The high natural fertility is indicated by high saturation of the cation exchange capacity by calcium and magnesium cations.

Old soil orders: Ultic Soils, Granular Soils, and Oxidic Soils

Amongst the rolling land and hills from Northland to the northern Waikato extensive areas of landforms have escaped erosion or deposition of widespread volcanic ash deposits for more than 50 000 years. Small areas occur in Wellington, Marlborough and Nelson. The comparative stability of these areas in New Zealand has enabled soil development to proceed to more advanced levels of weathering and leaching than in other parts of the country. Long and advanced weathering and leaching are expressed in very high clay contents, acidity, and very low natural soil fertility. Examples of Ultic Soils, Granular Soils and Oxidic Soils are shown in Figures 13, 14, and 15.

Oxidic Soils — Oxidic Soils are our most strongly weathered soils. They are clayey soils formed by weathering over extensive periods of time in volcanic ash or dark coloured volcanic rock. Despite high clay contents the soils are friable with low plasticity and fine structure. They contain appreciable amounts of iron and aluminium oxides. Oxidic Soils are only known in the Auckland and Northland regions. Parent materials are derived from strongly weathered andesite, dolerite or basalt rock or ash. The soils cover <1% of New Zealand.

Oxidic Soils have limited rooting depth, well-developed and relatively stable structure, slow permeability, and moderate or rapid infiltration rates. Clay contents range from 50% to 90%. Soil water deficits are common in summer. The soils have low reserves of potassium, magnesium, calcium and phosphorus. The clays have low cation exchange capacity at the natural pH of the soil, and phosphate retention is high. Contents of iron and aluminium oxides are high with low capacity to retain nutrients but the soils can be very productive when well-managed, as in the orchards of the Bay of Islands.

Granular Soils — Granular Soils are clayey soils formed from material derived by strong weathering of volcanic rocks and tephras mostly older than 50 000 years. Dry or moist soil samples may be easily parted into small hard fragments. When wetted and rubbed between the fingers the clay becomes sticky and may be easily remoulded with little cracking. The soils occur only in the northern North Island, particularly in the lowlands of the Waikato and South Auckland regions. Parent materials are usually strongly weathered. Granular Soils cover 1% of New Zealand.

Polyhedral structure is usually well developed but the soils are slowly permeable and have limited rooting depth. Topsoils have limited workability when wet. Natural nutrient reserves of phosphorus, potassium and magnesium are low. Clay minerals are dominantly kaolin-group minerals, with some vermiculite. Extensive areas under horticulture at Pukekohe demonstrate the productivity of these soils when they are well managed despite high clay contents, stickiness when wet and low natural fertility. The soils, however, are subject to erosion under long-term cultivation. The name 'Granular' is a reference to the well-formed soil structure that is frequently present.

Ultic Soils — Ultic Soils are strongly weathered soils that have very high clay contents throughout the profile. However, immediately beneath the topsoil a horizon frequently occurs with some depletion in clay and lighter colour. This is underlain by clay-enriched subsoil. The soils are weathered from mainly quartz-rich sedimentary rocks, are acid and strongly leached, and have generally low levels of calcium and other basic cations. Ultic Soils are most common in the northern North Island, and uncommon in Wellington, Marlborough, Nelson and Southland regions. Ultic Soils cover 3% of New Zealand.

The clayey subsoils have slow permeability and may become wet in winter. The upper horizons may be dispersive and susceptible to livestock-treading damage and prone to erosion. The soils are strongly acid with low nutrient reserves. Kaolin and vermiculite are the dominant clay minerals. The Ultic Soils are the 'yellow clay' soils well known to Auckland gardeners that are hard in summer and very wet in winter. Lime can correct the acidity, and compost can correct the heavy-clay-influenced structure.

NEW ZEALAND SOIL DATA

Inherent and dynamic soil properties

Some soil properties vary very slowly in time – for example the content of clay or stones. These are 'inherent soil properties' and are regarded as fixed in a human timescale. Others vary daily (e.g. soil water content) or over a period of 5–10 years (e.g. total soil organic carbon). These 'dynamic soil properties' are responsive to human management or short-term environmental drivers.

Point data – the National Soils Database

Point data are data collected from a grid-referenced site, in the landscape, and describe the soil profile at that point by field measurements and laboratory-analysed properties from samples. The National Soils Database (NSD) holds the primary national collection of point data. From it we have derived our soil classifications, interpreted our soil maps, developed our land management models, and our understanding of how soil properties vary with geology, rainfall, vegetation, topography and land management across the major gradients of the New Zealand landscape. It is the fundamental dataset that underpins our knowledge of New Zealand soils.

The NSD includes both inherent data and dynamic data. It has to be remembered that the dynamic data represent the state of the soil at the time of sampling and this needs to be taken into account in the way it is used.

The NSD comprises a dataset for a soil at a site, and there are more than 1500 sites in New Zealand (not counting other sites from New Zealand awaiting data entry, the Pacific Islands, and Antarctica). At each site the soil profile was described from a pit exposure following the methodolgy of either *Soil Survey Method* (Taylor and Pohlen 1979) or S*oil Description Handbook* (Milne et al. 1995). Samples were collected from all or some of the soil horizons, and analysed either in the Landcare Research Environmental Chemistry Laboratory (in Palmerston North) or previously by the DSIR Soil Bureau Laboratory. All profiles have at least soil chemical analyses for a number of soil horizons. A few soils have the complete set of moisture retention, mineralogy, X-xay flourescence analyses, and particle size. The NSD itself is a set of read-only tables of data that have undergone a structured check and authorisation process. The NSD also includes a physical archive of samples of nationally significant soils dating from the 1930s. These archive samples are housed in Palmerston North in a purpose-designed storage shed, with air-dry 2-mm-sieved soils retained in glass jars.

Access to the NSD

The primary legacy NSD dataset comprises yellow cards of field-collected data and white cards of laboratory-derived data. This is held at Landcare Research in Palmerston North. This primary dataset is not generally available in its physical form but the data are accessible by the following routes.

1. Digital versions of the original field and laboratory data cards are available through the Landcare Research Intranet.
2. These same data are accessible via the Landcare Research network from an SQL Server database to query and download datasets for data analysis.
3. A Paradox version of the NSD has been provided on a CD and distributed under licence to users.
4. NSD data are publically available on the following website. It provides a subset of the more commonly used soil attributes http://soils.landcareresearch.co.nz/contents/SoilData_NSD_About.aspx?currentPage=SoilData_NSD&menuItem=SoilData

The database is being rebuilt to provide a new and more accessible NSD data service.

Map data

Conventional soil maps show inherent soil properties because they remain sufficiently stable to reliably map them. However, maps can be made of statistics of variation of dynamic properties, for example, mean values or probability of exceeding a threshold.

Soil survey in New Zealand from 1938 to 2001 has resulted in a set of soil maps of varying quality at a range of scales, and patchy distribution. Many soil surveys included a soil bulletin in which the mapped soil series were qualitatively described. Most of these soil maps have been made under guidelines defined in *Soil Survey Method* (Taylor and Pohlen 1970) and *Soil Description Handbook* (Milne et al. 1995). The main limitations of these soil survey data include incomplete national coverage, regional inconsistency, varying standards, proliferation of soil series, and paucity of information directly useful for land management.

To provide a generalised national coverage of soil data, polygons from the *New Zealand Land Resource Inventory* (NZLRI) were populated by data from the NSD and expert knowledge. Fifteen soil-property maps were generated, collectively known as the fundamental soil layers (FSL) (Wilde et al. 1999). The NZLRI and FSL data are available for GIS download and viewing at http://lris.scinfo.org.nz/#/layers/global/oceania/new-zealand/ http://ourenvironment.scinfo.org.nz/home.

The NZLRI soil data used in this compilation were based on a map scale of 1:63 360, from a range of soil maps, mostly pre-dating 1979. This required simplification of more-detailed survey polygons; consequently NZLRI does not contain the best available map linework. In extensive areas the only source of information is the General Soil Survey maps of New Zealand (1:253 440 scale) (Lilburne et al. 2013). These have had extensive use as they are still the only source for complete national coverage of spatial soil data.

S-map

S-map had been initiated to provide ready web access to much-improved information for all New Zealand soils. Goals include consistent quality achieved by centralised curation and quality assurance, provision of data outputs to match the inputs of commonly used land management models, and the replacement of paper maps and reports by electronic products, with digital map outputs at resolutions equivalent to 1:50 000 scale or more detailed. Because legacy soil information was wrapped in arcane technical language and buried within grey literature, an important feature of S-map is the generation of soil fact sheets to provide comprehensive information for all mapped soils. These are immediately available when viewing the web service soil maps. Further development of the system will provide specialist

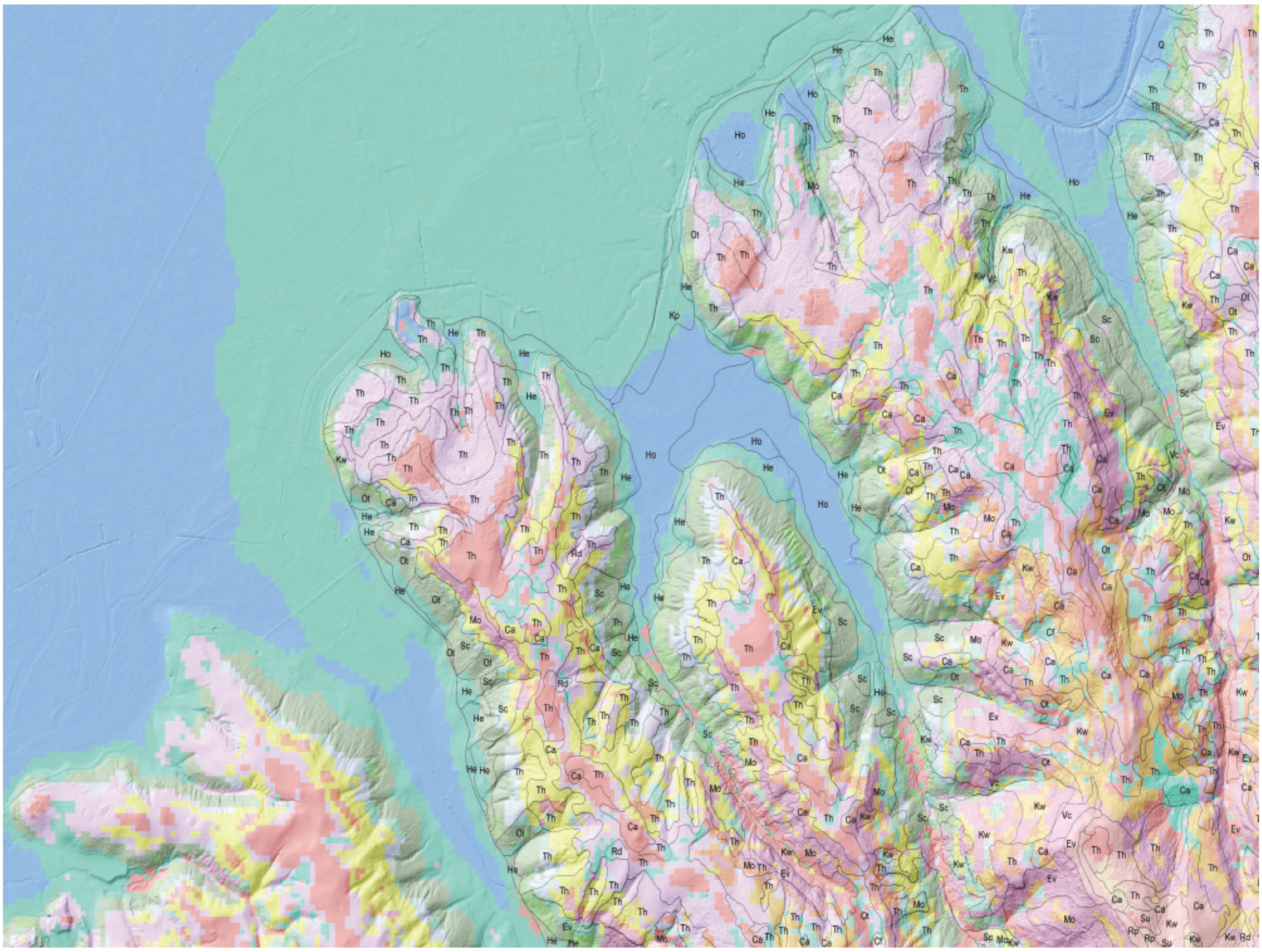

FIGURE 17 Portion of a soil map of the Port Hills, Christchurch (James Barringer, pers. comm.). The Black lines and symbols are from the original soil survey (Trangmar and Cutler 1983) where the soil distribution is presented as polygons. The coloured areas show an alternative raster depiction of the soil types that was modelled by data mining of the original soil survey. There appear to be more soils depicted in the raster map than the polygon map. This is because the polygon map has used only the dominant soil as the polygon label.

factsheets and use of more user-friendly language.

Completion will provide New Zealand with one national soil map with one national soil legend. This has required the harmonisation of legacy soil survey data by defining soil functional horizons (Webb and Lilburne 2011) and description of legacy soil profile data in these terms. The New Zealand Soil Classification (Hewitt 2010) has been extended by the definition of soil family and soil sibling categories to achieve the national soil correlation of soil names. Other features include probability distribution functions for key soil morphology attributes within soil classes, and estimates of uncertainty for most output attributes.

The S-map Online website (http://smap.landcareresearch.co.nz/home) works like Google Earth where one can zoom into an area of interest, turn on various kinds of information layers, and in the landscape see symbols for the soil types present. A left-click of the mouse brings up a summary of soil siblings in an area, and a further mouse-click opens a soil factsheet providing detailed information.

The state of our national soil knowledge

A comprehensive stocktake of our national soils is incomplete. We know the general categories of our soil orders as outlined in this chapter, but to capture the important soil variation a quantitative stocktake is necessary at the soil family and sibling levels of the soil classification. This awaits completion of the S-map project. Until then our stocktake will be limited to the areas already covered by S-map.

Polygons and rasters

Most currently available soil maps are conventional polygon maps. Soil variation in the landscape is described by delineating areas of similar soil variation by a line (a polygon). The polygon is labelled with the soil type names contained within the polygon. A raster soil map instead superimposes a grid (or raster) of cells (or pixels) over the landscape and provides a prediction of some target variable – a soil type or a soil property state within each pixel. The map is modelled from observation data points and superimposed covariate maps of geographic variables that covary with the target variable. The main advantage of raster over polygon maps is that they more realistically portray the smooth variation of soils across a landscape than the stepped portrayal of polygon maps (Figure 17).

SOIL CONDITIONS AND TRENDS

Applying inherent and dynamic soil data

Inherent soil data help answer questions such as ‘where is the location of land best suited to this specific land use’, or ‘what is the most suitable land use for this specific area of land’. These are questions about the impact soil types have on land uses. Productivity and sustainability may be maximised by locating a good fit between an enterpise’s land use requirements and the qualities the land can deliver. For example, if an enterprise requires irrigation, then soil that has good profile available water capacity will most likely maximise profit and minimise leaching loss of contaminants to groundwater. The presence of soil features such as high gravel content, hard pans, high watertables, high flooding risk, or erosion risk are identified in soil databases. It is an advantage to establish an enterprise with 'eyes wide open'. Where there is poor fit beween land use and soil attributes then extra land development and maintenance management costs are necessary. Land capability (Lynn et al. 2009) or land use suitability (Rossiter 1996) systems are available to identify land with a good fit between land use and soil.

Dynamic soil data indicate soil quality. Most land management practices impart some effect on the soil, for example, withdrawal of nutrients or compaction of soil structure. Working in the opposite direction to inherent properties, dynamic properties display the impacts of land use on soil types. Soil dynamic properties that are sensitive to land management pressure are selected as indicators for soil health assessment.

The capability of New Zealand's land resources

Land Use Capability system – The Land Use Capability (LUC) system has been in use since 1952 and remains an important tool in sustainable land management (Lynn et al. 2009). It is based on a land resource inventory of soil, land slope, vegetation, rock, and erosion. Assessment of these factors is used to assign land units to one of eight LUC classes. These indicate the general capability of the land for sustained production, and is an expression of land use versatility. LUC classes are subdivided into LUC subclasses, which indicate the dominant physical limitation, and LUC units, which group similar landscapes. Spatial LUC information is available for GIS download at http://lris.scinfo.org.nz/#/layers/global/oceania/new-zealand/

Our best soils – These are called 'versatile' or 'high class soils' and are the soils that would be regarded as having the highest soil natural capital. National analysis of our most versatile soils shows the area is limited to about 5.5% of the area of New Zealand. These soils are most common among the Recent and Allophanic Soils. They are also found among the other soil orders, but least among the Podzols, Raw Soils, Anthropic Soils and Brown soils that are strongly acid or on steep hills or mountains.

Because high class soils have such limited extent in New Zealand it has been argued that they should be reserved for intensive horticultural and agricultural production and not compromised by non-agricultural uses like urbanisation. High class soils are efficient food producers as the full services of the soil are available to support plant growth. However, there are conflicts over land use priorities because towns and cities are frequently located on alluvial land where high class soils are concentrated.

Soil natural capital – Quantification of soil natural capital has potential to provide a new method for evaluating land in a manner that will help place soils in an economic context. A stock adequacy approach to quantifying soil natural capital has been proposed (Hewitt et al. 2012) that considers the set of soil services needed by a land use for it to perform optimally. These soil services are in turn supported by the underpinning soil natural capital stocks. Performance of those stocks requires that they are adequately topped up. The response of the service to the stock is modelled and the soil natural capital adequacy is expressed in a percentage scale.

Soil quality in New Zealand

The science literature uses the term 'soil quality' rather than 'soil health' because 'health' is encumbered by wide shades of meaning, however, literature on the state of the environment may use the terms interchangeably. The European Commission definition of soil quality (Wikipedia) is the soil's ability to provide ecosystem and social services through its capacities to perform its functions under changing conditions.

Soil quality monitoring – Over the last century agriculture has massively changed many of our soils that were originally poor for farming. Acidity has been corrected by liming, low fertility by fertilisers, drought by irrigation, wetness by drainage, and subsoil pans by deep ripping. These and other interventions have contributed greatly to our national prosperity and to increasing intensity of land use. More intensive production, whether by horticulture, cropping or dairying, raises the issue of sustainability. Can the soil services that we rely on be sustained without loss of soil quality and effects on the wider environment? These are the motivations for soil quality monitoring.

Systematic soil quality monitoring in New Zealand was initiated at a regional scale by Sparling and Schipper (2002, 2004) with the selection of seven soil quality indicators: total carbon, total nitrogen, pH, Olsen phosphorus, mineralisable nitrogen, bulk density, and macroporosity. These were based on dynamic soil properties that provided interpretation of biological (related to soil organic matter reserves), fertility, chemical and physical qualities of soil under a range of land uses and soil types relevant to New Zealand (Sparling and Schipper 2002; Lilburne et al. 2002; Sparling et al. 2003, 2004). A system was developed to interpret monitoring results by defining target ranges for the indicators and implemented through the SINDI website (Lilburne et al. 2000; http://sindi.landcareresearch.co.nz/; Sparling et al. 2008). The indicator focus was on soil condition and did not include erosion or soil contamination (apart from an Olsen phosphate indicator of excess phosphorus).

Concurrent research on an extended set of indicators at the paddock scale (e.g. Beare et al. 1999) derived target ranges based on production values and these were implemented through the then Crop and Food Research SQMS website (http://www.plantandfood.co.nz/page/our-research/sustainable-production/products-systems/land-management/)

Soil quality reporting – A review of soil quality indicators after 12 years of monitoring in the Waikato Region (Taylor et al. 2010) concluded that the existing key soil quality indicators were useful for state of the environment monitoring in the region and were able to define five key regional issues of soil quality: soil compaction, topsoil organic matter decline, excessive fertility, erosion risk, and accumulation of contaminants. Regional council soil quality monitoring has been reviewed by Hill et al. (2003) and the Land Monitoring Forum (2009). Regional-scale state of the environment reports are usually available through regional council websites. The most recent national statement of soil quality is the *Environment New Zealand 2007* report by the Ministry for the Environment (2007).

SPATIAL DISTRIBUTION OF NEW ZEALAND SOILS

Principles of soil spatial distribution

Early 20th century observations of spatial variation in soil types were elegantly expressed by Jenny (1941) in the expression $s = f(cl,o,r,p,t)$. This states that the nature of the soil (either soil class, or soil property) is a function of five soil-forming factors: climate, organisms, relief, parent material, and time. Any significant change in one of these factors will change the nature of the soil. Jenny, and many others, demonstrated systematic changes in soil relative to individual soil factors, but no solution was found for the complete expression. It was the

FIGURE 18 A temporally arrayed soil pattern where soil properties are strongly related to age of the land surface since it was either eroded or deposited. Soils on the ridges are relatively stable and show relatively advanced weathering but may also at some time become eroded.

development of spatial applications in statistical modelling that enabled McBratney et al. (2003) to solve the expression in the context of digital soil mapping. Jenny's expression was restated as the 'scorpan' model, $S = f(s,c,o,r,p,a,n)$, where S can be soil classes or soil attributes, s is other soil classes or attributes, c is climate, o is organisms, r is relief, p is parent material, a is age, and n is spatial position in (landscape) space. In digital soil mapping the factors are covariate layer inputs to a spatially applied model of the variation of soil classes or properties in a landscape.

The raster map in Figure 17 is a New Zealand example of a scorpan approach to soil mapping. Digital soil mapping is proving to be a crucial tool in soil resource inventory. It is still important, however, to develop understanding of soil spatial relationships by recognising conceptual models of soil patterns. In the following section a highly generalised soil pattern of New Zealand is described at a national scale, and two important types of soil pattern are briefly described that occur at hillslope scale.

National- and regional-scale soil patterns

At a highly generalised national-scale New Zealand can be partitioned into four soil order-associations.

- Soil order-association 1 comprises the northern areas of Northland, Auckland, and northern Waikato. The land has been relatively stable tectonically for periods long enough that the ancient soil orders – Oxidic Soils, Granular Soils, and Ultic Soils – dominate.
- Soil order-association 2 comprises the central North Island. Soils have been rejuvenated by additions of volcanic ejecta. The soils are Allophanic Soils, Pumice Soils, and Recent Soils formed in young volcanic materials close to active volcanos.
- Soil order-association 3 comprises the steep and high mountains of the North Island and South Island. They are dominated by active erosion and sedimentation with rock debris, wind-blown loess, and peri-glacial patterned ground features. The soils are Raw Soils, Recent Soils, Brown Soils, and Gley Soils. Allophanic Soils may be present but Allophanic Brown Soil groups of the Brown Soil order are common. Allophanic soil material, which is usually associated with volcanic ash, is also formed from the rapid weathering of greywacke debris in the South Island mountains.
- Soil order-association 4 comprises the rest of New Zealand where soil development has been rejuvenated by disturbance such as erosion and sedimentation related to geological tectonic forces, glaciation and related cold-climate processes mainly in the Pleistocene. The regional distribution of soil orders relates strongly to climate gradients, and is best expressed in the dominant quartz-rich parent materials from greywacke, schist, and granitic rocks. The Semiarid Soils are confined to the lowlands of Central Otago and mid-Waitaki River Valley sheltered from prevailing rain by mountain ranges. The Pallic Soils are extensive elsewhere in lowlands and lower mountain slopes where summer soil water deficits are usual. The Brown Soils are extensive in the higher rainfall land. Podzols are the soils

of the acid-leaching forests under high rainfall. Brown Soils can occur in unexpectedly dry areas. In very permeable sand or sandy gravel, with low water storage capacity, the leaching required to develop these soils can be accomplished under a lower-than-normal rainfall.

Apart from the dominant soil orders that characterise the soil order-associations, there are other soil orders. The soil order-associations boundaries are transitional, and within them there are exceptions to the rule. In soil order-association 1, Brown Soils are recognised where slope movement has occurred on steep slopes, especially in steeplands. In soil order-association 2, Brown Soils and Pallic Soils are also present in hills or steeplands. In soil order-association 4, Ultic Soils occur on long-stable sites in some lower slopes of the Marlborough Sounds, old dissected alluvial terraces and granitic hills in Nelson, and old terraces in Southland.

Patterns of stability, disruption or inheritance

New Zealand is positioned in a highly active tectonic geological setting. The effects of tectonism are seen in the soil patterns on sloping land that show the effects of either relative stability or disruption by erosion or sedimentation, or the inheritance of variability imposed by the parent material substrate. Given relative stability, soils mature in time with weathering of minerals, and leaching of nutrients, and soil profiles show the differentiation of well-developed soil profile horizons. The nature of a soil at a site results from a dynamic interplay between these progressive forces, and the effects of instability that can reset (or rejuvenate) the soil development clock. Tonkin and Basher (1990) recognised two fundamental types of soil patterns (or arrays) in a landscape: the spatial array and temporal array.

In the spatial array, relationships between different soil profile types are spatially driven. An example is the catena. A catena displays systematic soil differences controlled by position downslope from hill crest to foot slope. The soils are genetically linked like a chain ('catena' in Greek means chain). This indicates that the soils have been stable sufficiently long for them to have become genetically linked, and their location can be predicted by slope position. Genetic linkages may involve any processes that drive soil differentiation, for example, the transfer of sediment or drainage of water downslope.

In a temporal array, relationships between the different soils are controlled by different soil ages (Figure 18). An example is an eroded mountainside, where soil types differ in time since they experienced either erosion or sedimentation. More-stable sites will have more-developed soil profiles, and younger sites will have less-developed profiles. Where patterns of erosion are chaotic, spatial location prediction for specific soils is challenging.

Within these two basic arrays there are a large variety of different soil patterns. These are used by soil surveyors in soil mapping to infer soil properties from observation sites. The inferences rely strongly on an understanding of the soil and geomorphic processes that have formed the pattern.

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