NSW GOVERNMENT

NSW FOREST MONITORING AND IMPROVEMENT PROGRAM

Soil health and stability monitoring in forests

Background and review of potential indicators

2 February 2021

Published by NSW Department of Planning, Industry and Environment

dpie.nsw.gov.au

Title: Soil health and stability monitoring in forests

Subtitle: Background and review of potential indicators

First published: 2 February 2021

More information

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Acknowledgements

The author acknowledges and appreciates the assistance provided by Dr Jonathan Gray, Dr Linda Henderson, Dr Mitch Tulau, Dr Ross Peacock and other members of the Natural Resources Commission who provided valuable comment and advice during the preparation of this review.

Cover image: DPIE soil scientist Mark Young describes a soil in a Hunter Valley forest. Photo: C Murphy/DPIE.

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1 Introduction

1.1 Research question

As part of the NSW Natural Resources Commission's Forest Monitoring and Improvement Program, one of the State-wide evaluation questions asked is: **what is the health and stability of soil in forests, and what is their predicted trajectory?**

Focus areas identified were:

- evaluating the effectiveness of forest management practices, including the road network, to minimise soil erosion and health in high risk areas
- simulating and forecasting soil health and stability under future scenarios
- monitoring key metrics to test and track thresholds, benchmarks and forecasted outcomes.

To help answer this question, the NSW Department of Planning, Industry and Environment (DPIE) and the University of Sydney commenced a project to deliver baselines, drivers and trends for soil stability and health in forest catchments. This literature review is a preliminary component of this project.

1.2 Objectives of this review

This document aims to:

- review the current available literature and research relating to indicators of soil health and stability in forests, including review of forest monitoring programs and policies at state, national and international levels
- review the relationship of soil health and stability indicators to forest management actions, such as fire, road construction and use, timber harvesting, grazing and protection, and to external major drivers of change —e.g. climate change, extreme weather events
- propose a provisional set of indicators for soil condition, health and stability in forests of NSW, to be used as a basis for development of a monitoring program and finalised set of measures of forest soil health and stability.

2 Background

2.1 What is soil health?

The Intergovernmental Technical Panel on Soils of the United Nations' Food and Agriculture Organisation (FAO) defines soil health as:

> the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems (ITPS 2020).

This review considers the terms 'soil quality', 'soil condition' and 'soil health' to be interchangeable and uses the same term as the original research or investigation being reviewed—the most commonly used being 'soil quality'.

A healthy soil typically supplies the essential nutrients, water, oxygen and support that plants need to grow and thrive in a particular environment. A healthy soil is also a dynamic living ecosystem, containing billions of microscopic and larger organisms that carry out a range of vital environmental functions. Figure 1 (below) describes the functions of a healthy soil.

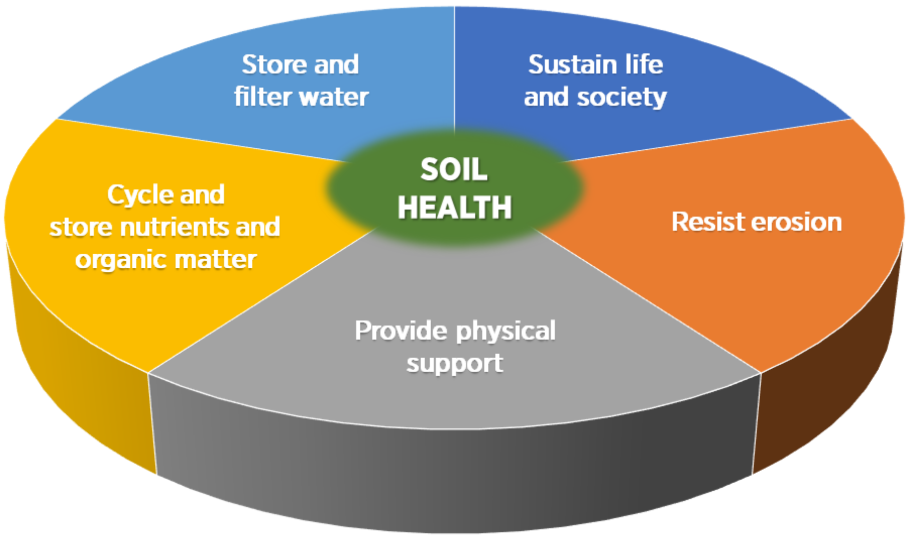


Figure 1. A schematic diagram showing the 5 main functions of healthy soils (modified from Agriculture Victoria 2020)

There is no one indicator of soil quality, but a number of measures can be used to quantify the soil's physical, chemical and biological characteristics. Choosing these measures is one of the most difficult parts of soil health assessment, as the choice of indices depends on a variety of concerns including feasibility, cost-effectiveness, accuracy and applicability. Soil health indicators selected for agriculture may not be wholly appropriate for monitoring soil health in forested environments, particularly in Australia where the relationships between soils and forests are quite unique (see Section 3).

Ideally, indicators of soil quality should be:

- quantitative and measurable
- responsive within the time scale specified
- interpretable
- cost effective
- scientifically justifiable
- socially acceptable
- internationally recognised
- preferably part of historical monitoring procedures

(Land Monitoring Forum, 2009).

2.2 Why is soil health important?

Whatever definition one uses, the importance of soil health is difficult to overstate.

On an environmental level, the quality and health of our terrestrial, riparian and estuarine environments are highly reliant on the health of our soils. Soil provides the medium, substrate, biological activity, nutrients and water for native vegetation to grow and thrive. Native wildlife is also reliant on soil health, whether they live above, on or within the soil, as they rely on native vegetation for their survival.

The quality of air and water also relies on soil health; healthy soils store water, buffering the environment against the effects of droughts, and filter that water as they release it, preventing pollution. Healthy soils mitigate against climate change by storing carbon, whilst soils which lack healthy functionality may be subject to erosion, releasing sediment and pollutants into waterways and dust into the air. Airborne dust contributes to carcinogenic outdoor air pollution where there is a close relationship between exposure to high concentrations of small particulates and increased risk of respiratory infections, heart disease and lung cancer (WHO 2018). Airborne dust in NSW over periods of 2019 has repeatedly broken records for activity and concentration, coinciding with historic lows in groundcover (Department of Planning, Industry and Environment 2019a, 2019b). Soil health is therefore also a human health issue.

On a human level, soil is the basis for our prosperity and survival, producing (directly or indirectly) around 95% of the food we eat. Healthy soils teem with life, converting minerals and organic matter into plant nutrients. Access to healthy, nutritious food depends largely on healthy soils, and the issues of national and global food security are intrinsically linked to soil health.

It has been estimated that in 2011 land and soil degradation cost the Australian economy some AU$5.74 billion, or around 12% of its total GDP. Since NSW produces around 33% of the nation's GDP, this equates to an estimated impact of degraded soil condition on the NSW economy in the same year of about AU$1.89 billion. Of course, soils also produce all of the timber we use in construction, paper and other industries, adding to its importance as an economic issue — in FY2017–18 forests contributed some AU$9.2 billion to the Australian economy (ABARES 2019).

In conclusion, the prosperity and survival of both the human and natural world is intrinsically and profoundly linked to the health of our soils.

2.3 What is a forest?

The 2018 *Australia's State of the Forests Report* (Montréal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018) defines a forest in Australia as:

> An area, incorporating all living and non-living components, that is dominated by trees having usually a single stem and a mature or potentially mature stand height exceeding

2 m and with existing or potential crown cover of overstorey strata about equal to or greater than 20%. This includes Australia's diverse native forests and plantations, regardless of age. It is also sufficiently broad to encompass areas of trees that are sometimes described as woodlands.

2.4 Applications of soil health in forests

The use of the soil health or soil quality concept has been applied most widely in the field of production agriculture—how to increase productivity in farming systems whilst maintaining or improving the condition of the soil. For example, the global system for measuring soil health, defined by the UN's Food and Agriculture Organisation (FAO), is effectively inherited from the FAO's Soil Qualities for Crop Production. However, due to fundamental differences between forest and agricultural soils (Attiwill and Leeper 1987), different methods and measures are required to assess forest soil health (see Section 3.2).

The concept has been applied to a lesser extent to more natural environments such as forests and rangelands. Several countries have implemented soil health monitoring and measurement as part of their forest monitoring programs, some of which have been running for many decades and provide a substantial knowledge base of soil condition and response to management practices and external agents of change (see Section 6).

These initiatives have been undertaken in varying levels of response to the international policy initiative of the 1990s known as the Montréal Process, which developed criteria and measures for sustainable soil management, monitoring and reporting in forestry operations. Examples of soil health monitoring in forests from around the world are described in Section 4, along with a more detailed description of the Montréal Process.

The NSW Government reports on the indicators for sustainable forest management defined by the Montréal Process as part of Australia's 5-yearly State of the Forests Report, though there are currently very few hard data on which to base this reporting. This is a knowledge gap that the NRC forest monitoring and improvement program aims to address.

A 25-year old plantation of Eucalyptus grandis *(flooded gum) in the former Mebbin State Forest, now National Park, in north-eastern NSW. Photo: NSW Forestry Corporation.*

3 Characteristics of NSW forest soils

3.1 Forests and soil distribution

Being the oldest, flattest and driest inhabited continental land mass, and dominated by ancient, nutrient-poor soils, Australia has developed a flora adapted to such soil conditions. Indeed, soil fertility and nutrient status are fundamentally important in controlling the distribution and function of Australian plant communities (Raison 1980).

The map in Figure 2 shows that the remaining forests of NSW are dominated by eucalypts and occur in a discontinuous belt along the eastern coast and adjacent ranges, with outliers in the semi-arid west and south-west. Forests in other areas of the central and eastern parts of the state have been extensively cleared for agriculture, whilst the far west is dominated by open-shrublands. Limited areas of temperate and subtropical rainforest occur in the coastal ranges of the north-east of the state, mostly now in protected areas.

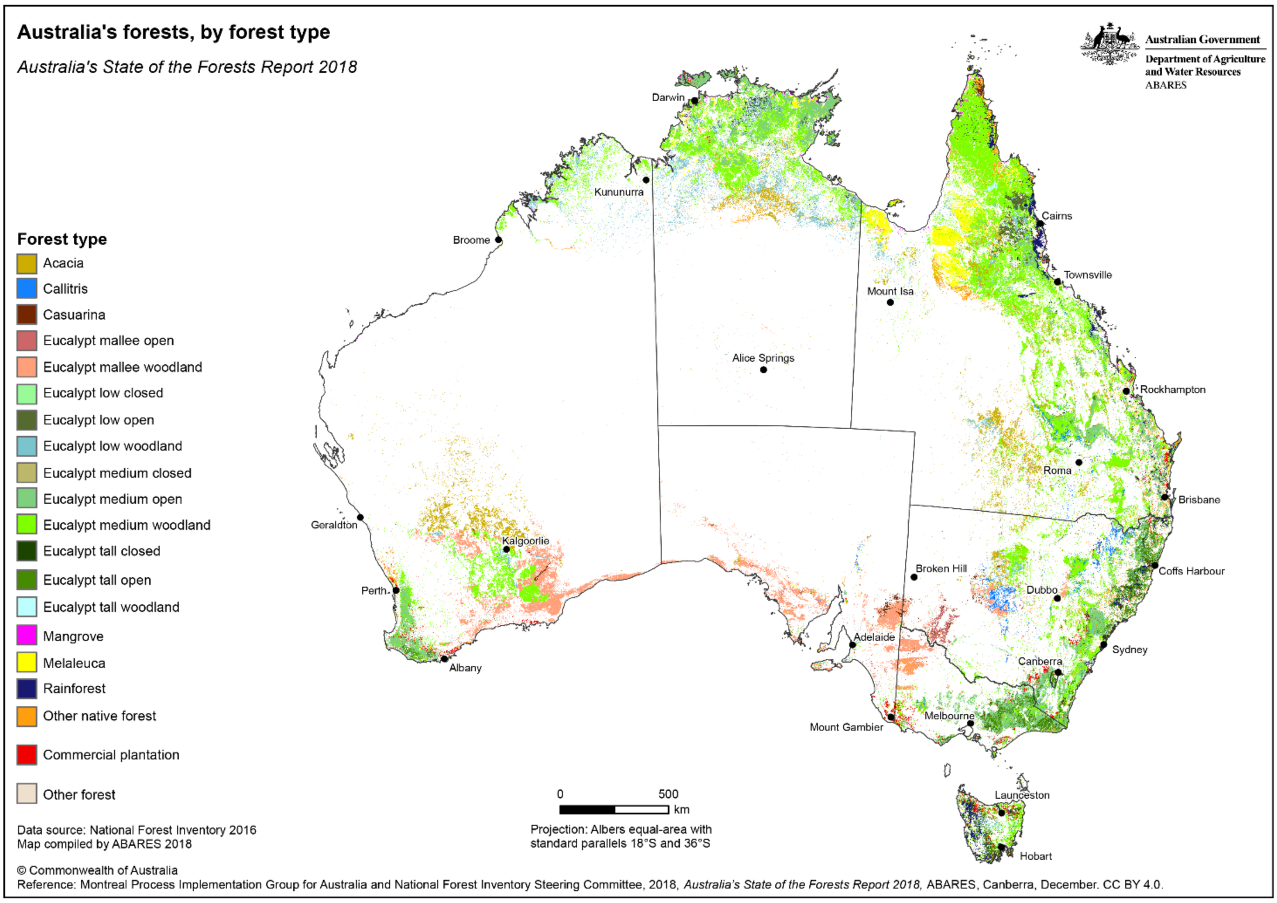


Figure 2 Distribution of forests in Australia (Montréal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018)

Figure 3 shows the distribution of soil types across the state, which reflects NSW's diversity in landscapes, geology and climate.

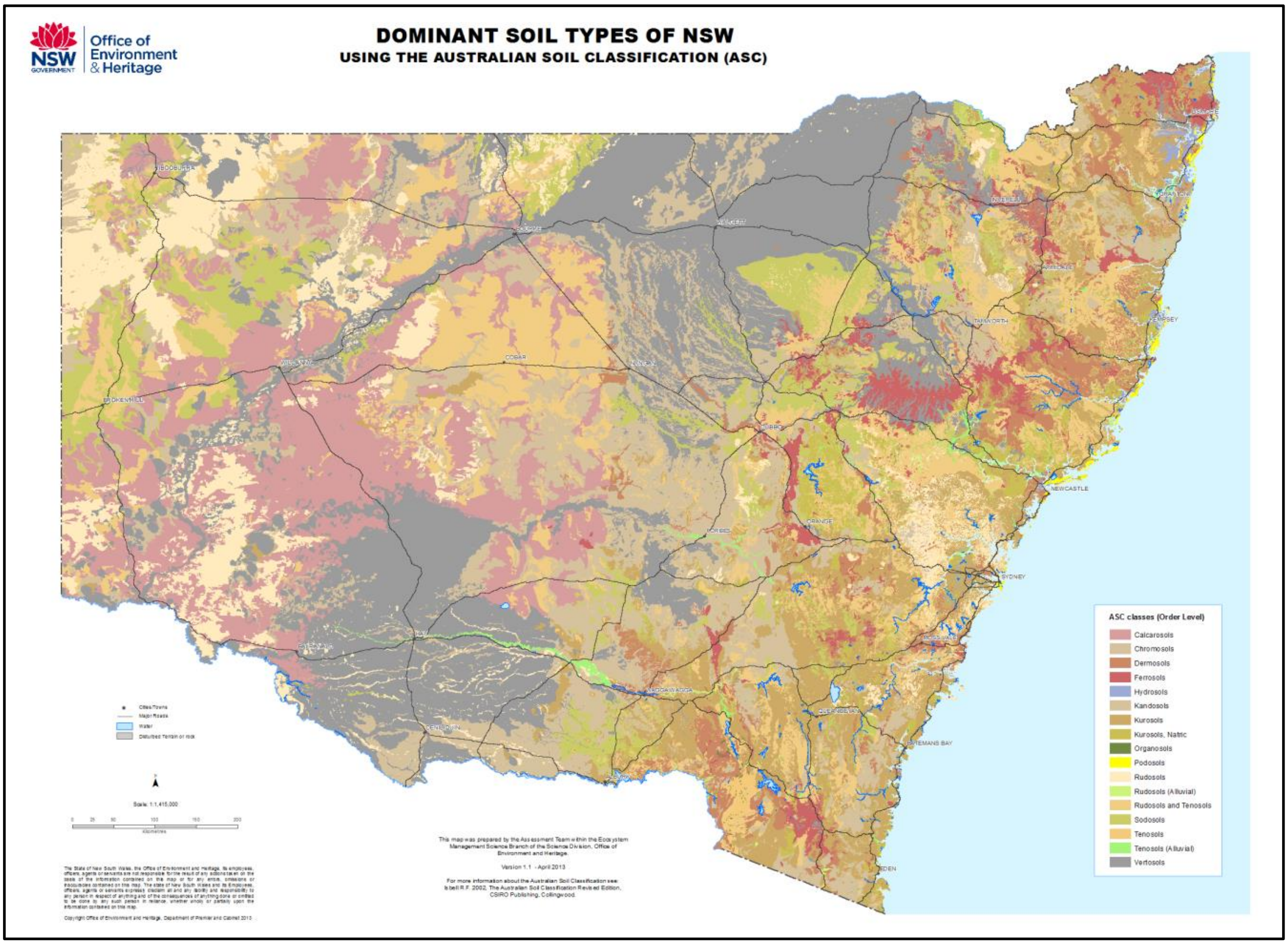


Figure 3 Dominant soil types of NSW

The remaining native forests of NSW grow across a variety of soil types, with their distribution affected primarily by climate. Those soils of high quality include Ferrosols, which are deep, fertile, well-structured soils developed on basic substrates such as basalt. Tall closed-forest, or rainforest grows on these soils in high-rainfall areas such as the North Coast region of NSW around Lismore, Dorrigo, Comboyne and Barrington. Rainforest also grows in sheltered locations such as deep valleys and south-facing slopes as far south as the central South Coast, and in restricted littoral locations on beach and barrier sands or on metasedimentary or volcanic-derived headland soils. In these areas, favourable microclimatic conditions contribute to vegetative vigour and species richness, which in turn positively affects soil quality. These forests are poorly adapted to fire.

The great majority of forests in NSW are dominated by eucalypts, hardy plants that evolved from rainforest ancestors to adapt to environments where drought, nutrient-poor soils and fire were increasingly common (Montréal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018). Areas where rainfall exceeds 1 000 mm/year but where soils are of lesser quality, such as Kurosols (acidic texture-contrast soils) and Dermosols (soils with only gradual increase in texture, but with structured subsoils) support tall closed-forest dominated by eucalypts, also known as wet sclerophyll forests. These have a tall eucalypt overstory (often >30 m) that provides >80% crown cover, and a soft-leaved, dense understory that may resemble that of a rainforest, though this may be destroyed by fire. These forests are limited in extent in NSW and historically have been extensively logged for high-quality timbers.

Much more extensive are the open-forests and tall open-forests dominated by eucalypts, also known as dry sclerophyll forests. These grow on a variety of soil types across eastern NSW where rainfall is 500 – 1 000 mm/year, including Kurosols, Dermosols and Kandosols (moderately to strongly acidic soils of gradual texture contrast but with massive subsoils), and have an overstory of 10 – 30 m height, providing 50 – 80% crown cover, and either a grassy or shrubby, hard-leaved understory. Areas with poorer soils, such as Rudosols and Tenosols that are shallow, rocky and/or sandy, support eucalypt open-forest and woodland, typical of which are the forests growing on sandstones around the Sydney Basin. These forests occur extensively in the eastern ranges, slopes and tablelands of NSW and are adapted to both drought and fire.

To the west, in areas with rainfall <750 mm/year, open-forest and woodland dominated by species of Acacia, including the brigalow (*Acacia harpophylla*) forest that is widespread through northern NSW on flat to undulating lands with Vertosols, which are deep, cracking clay soils.

In low-lying areas with poorly drained Hydrosols along the NSW coast and adjacent estuarine floodplains, Melaleuca low woodlands are found, whilst mangrove forests grow in intertidal areas.

3.2 Distinctiveness of Australian forest soils

There are significant functional differences between agricultural and forest soils, particularly in terms of nutrient cycling and availability (Attiwill 1999). This is a result of the very different timescales over which 'production' from these soils occurs.

In agricultural soils, nutrient availability (with the exception of N) is an immediate issue on a timescale of weeks to months—the timescale on which planting, crop growth and harvesting occurs—meaning that nutrient cycling from plants to soil and back does not usually have time to occur. Moreover, removal of the most nutrient-rich parts of the crop at harvesting leaves only the parts with low nutrient concentrations left to be cycled into the soil as organic matter. Nutrient cycling through natural biological processes cannot be effective in continuous cropping systems, and external addition of nutrients through fertiliser and other ameliorants is frequently required to maintain soil productivity.

Conversely, nutrient availability in forest soils is a long-term issue involving both organic and inorganic processes over years, decades or even centuries—the timescale on which trees seed, grow to maturity and are then (in the case of a production forest) harvested or (in the case of a natural forest) die. The disparity between these options may be considerable—whilst plantation softwood species such as *Pinus radiata* (radiata pine) are harvested at about 35 years of age, mature examples of species such as *Eucalyptus regnans* (mountain ash) can be well over 300 years old. The inherent nutrient status of the soil, the soil's unique chemistry, the soil's interactions with climate, atmosphere, lithology and biology, and the soil's own biota, are much more important on these timescales. Therefore, different measures of soil functionality and health are required.

In this context, Attiwill and Leeper (1987) observed that "too little basic research, and too little research on our native forests" had been done, and that it was consequently impossible to determine whether forest soils' supply of nutrients is sufficient to sustain forest diversity and productivity, particularly in the face of significant disturbance such as harvesting and bushfires. Nor was it possible to quantify forests' potential role in C sequestration as part of climate change mitigation. These 2 issues are of particular concern with regard to native forests, as most study of the preceding years was focussed on soils in plantation forests. Attiwill (1999) called for an increase in basic research in the eucalypt forests of Australia.

3.3 Threats to Australian forests and soils

Soil fertility and nutrient supply are fundamental factors in controlling the functioning and distribution of plant, and therefore, faunal communities (Raison 1980). In terms of the plant-soil ecosystem, nutrient enters through only a limited number of pathways (DeBano *et al*. 1998):

- precipitation
- dust fall
- N fixation
- geochemical weathering of rocks.

Nutrients may also be moved from site to site through deposition of materials via overland flow.

In many Australian ecosystems, a significant proportion of nutrients are stored in living organic matter rather than in the soil (Raison 1980), particularly in rainforests. Nutrients cycle from vegetation back to the soil through processes such as leaf and litter fall and decomposition; and nutrients may be lost permanently from the system through leaching, soil erosion or (in certain circumstances) denitrification. In undisturbed ecosystems these rates are generally low (DeBano *et al*. 1998), though disturbances such as fire and forestry activities can dramatically increase them.

Fire is a natural component of Australian ecosystems (Gill 1974). Australian forests are highly adapted to fire, possessing well-developed response mechanisms which ensure post-fire recovery (Cary and Banks 2000). Human activity, however, has had a major influence on fire regimes (Russell-Smith *et al.* 2007), with contemporary impact differing markedly from those under Aboriginal occupancy (Bowman 1998). Climate change has a strong potential to further alter these regimes, increasing severity and area burned in temperate forested regions (Bradstock 2010).

A review by Tulau and McInnes-Clarke (2015) concluded that, though measurement is difficult, the effect of fire on soil health is often significant through its disruption of the normal nutrient cycling process acting in forest environments, removing nutrients through processes such as vaporisation, convection (in smoke), leaching and post-fire soil erosion.

Fire have a significant effect on forest ecosystems and the soils that support them.
Photo: H Milford.

Fire also has a significant effect on the carbon cycle. Fire diminishes topsoil fertility (Tulau and McInnes-Clarke 2015) and the occurrence of fires in both undisturbed and agricultural ecosystems can produce long-lasting effects on soils' organic matter composition and dynamics (González-Pérez *et al.* 2004).

Moreover, as Attiwill and Leeper (1987) observed, much of the organic matter in soils is very old, and natural decomposition to inorganic constituents can take centuries to millennia. Thus, major disruptions of the C cycle caused by fire can last for decades or even centuries (Bowd *et al.* 2019, Tulau and McInnes-Clarke 2015).

As virtually all of the N in a soil is located in its organic matter, its loss through fire therefore profoundly affects the soil's N status (Tulau and McInnes-Clarke 2015). Fire has less of an effect on soil P as its volatilisation threshold temperature is significantly higher than N (774°C vs 200°C) and it is converted to insoluble orthophosphate that binds to Al, Fe and Mn oxides, particularly in acidic soils (Tulau and McInnes-Clarke 2015). The effect of fire on micronutrients is less well understood, but in general it is considered that the nutrient pool of topsoil fertility is diminished by fire, and any nutrient loss is usually significant for Australian forests given the poor nutrient status of the soils on which they grow. Given that even low-intensity fires can have an effect, frequent repeated low-intensity burning is likely to cumulatively deplete soils of nutrients and interrupt nutrient cycling (Raison 1980).

Orians and Milewski (2007) have suggested that the unique characteristics of many Australian ecosystems are the evolutionary consequence of adaptations to nutrient poverty, compounded by intense fire that tends to occur as a result of nutrient poverty. Their 'nutrient-poverty/intense-fire theory' postulates that plants growing in nutrient poor soils build carbohydrates into well-protected, long-lasting, nutrient-poor foliage and plentiful lignified tissue. In turn, the resultant accumulation of nutrient-poor biomass combines with low rates of herbivory to provide fuel for intense wildfires, which further exacerbates nutrient poverty. This theory directly links the natural quality of Australian forest soils to the characteristics of its native forest vegetation.

In the case of production forests—whether of native hardwood or introduced softwood—the activity of harvesting timber has a significant site-based effect on soil. This includes soil excavation, disturbance and mixing, compaction and structural decline, and exposure to erosive elements, chiefly water.

Eucalypt dieback, referring to the chronic, widespread decline of eucalyptus trees, has also become a threatening process in many of Australia's forest and woodland (Jurkis 2005). The causative factors are as yet not fully understood (Ross and Brack 2017), but dieback tends to occur in landscapes that have already been disturbed and thus where the ecosystem is already dysfunctional. Numerous common forest types are affected. Factors identified as related to canopy dieback include water deficit, soil salinity, damage caused by psillids and associated bell miners, exotic pathogens, increased soil moisture and long-term N accumulation, and variations in soil nutrient availability caused by altered fire regimes and artificial fertilisation (Jurskis 2005). Further research into causative factors and remedial action is required.

Beyond these more site-based threats is the regional and global threat of climate change. Climate has long been recognised as a significant factor controlling soil properties, and climate change will impact plant growth in both agricultural and native ecosystems— Australia has warmed on average by 1.44 ± 0.24 °C since national records began in 1910, with most warming occurring since 1950 and every decade since then being warmer than the ones before (Commonwealth Science, Industry and Research Organisation and Bureau of Meteorology 2020), indicating that impacts have already begun. Impacts of climate change on Australian forests include: increasing temperature and moisture stress; increased risk of drought and lower rainfall in some areas; changes in species distribution and loss of biodiversity at higher altitudes; increased risk of damaging or catastrophic wildfire; greater impacts from introduced weed species. In regions with more consistent rainfall, productivity may increase under elevated CO2. However, it is likely that water and nutrient availability will limit productivity increases, particularly when combined with higher temperatures (Keenan 2017).

In terms of soils, digital soil modelling has suggested that soil organic C will decline while pH and sum-of-bases will increase, although this modelling does not (as yet) include changes or feedbacks from any change of vegetation, or any changes in land management, nor impacts of extreme weather events (e.g. droughts, storms) made more severe by climate change (Gray *et al*. 2019).

The 'overlay' of climate change effects over these other issues further increases the need for ongoing monitoring of forests and their soils in NSW.

4 Policy frameworks

4.1 A global perspective: the Montréal Process

The 1992 United Nations Conference on Environment and Development (the 'Earth Summit') in Rio de Janeiro called on nations to ensure environmentally sustainable development. A year later, an international seminar was held in Montréal, Canada, that focused on sustainable management of forests. From this conference, the Working Group on Criteria and Indicators for the Conservation and Sustainable Management of Temperate and Boreal Forests ("Montréal Process") was formed, which sought to develop internationally agreed criteria and indicators for sustainable management of forests.

The decided criteria included one criterion for forest soil resources, and 4 associated indicators:

- area and percentage of forest land with significant soil erosion
- area and percentage of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties
- area and percentage of forest land with significant compaction or change in soil physical properties resulting from human activities
- area and percentage of forest land experiencing an accumulation of persistent toxic substances.

Gale and Cadman (2014) investigated the development of these criteria and the subsequent indicators produced under the Santiago Declaration (see Section 4.2) and determined that the system originated in a policy network centred in the Canadian Forest Service and Canadian Council of Forest Ministers. This gave, in their view, the definition of sustainable forest management agreed under the Montréal Process an 'economistic' slant. Whilst Canada's forest policy network was under pressure to demonstrate its environmental and social credentials, its proposed policy framework emphasised the growing and harvesting of timber over the protection of biodiversity, Indigenous peoples and community livelihoods (an 'eco-social' approach) and was carried through virtually unaltered into the Montréal Process.

A more 'eco-social' norm emerged from a non-government consultative process that in 1993 set up the Forest Stewardship Council, FSC (see Section 4.4).

4.2 Regional application: the Santiago Declaration

Australia is a member of the Montréal Process Working Group (MPWG), which consists of a small group of forestry representatives from 10 non-European nations (European nations having followed their own process—see Section 4.3). The Group produced a set of criteria and indicators for forest conservation and sustainable management, which is known after the place of the MPWG's first meeting in 1995 as the Santiago Declaration.

The Santiago Declaration defines 7 sustainability criteria and 67 indicators. Soils in forests are addressed under the fourth criterion, named 'Conservation and Maintenance of Soil and Water Resources'. Under this goal, 7 indicators are defined:

4a Area and percent of forest land with significant soil erosion
4b Area and percent of forest land managed primarily for protective functions
4c Percent of stream kilometres in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation

4d Area and percent of forest land with significantly diminished soil organic matter and/or changes in other soil chemical properties
4e Area and percent of forest land with significant compaction or change in soil physical properties resulting from human activities
4f Percent of water bodies in forest areas with significant variance of biological diversity from the historic range of variability
4g Percent of water bodies in forest areas with significant variation from the historic range of variability in pH, dissolved oxygen, levels of chemicals, sedimentation or temperature change
4h Area and percent of forest land experiencing an accumulation of persistent toxic substances.

4.3 Another regional application: the Helsinki Process

Beginning in 1990, the Helsinki Process proceeded independently despite the ongoing development of the Montréal Process and Santiago Declaration. Following a series of conferences in the 1990s involving ministerial representation from across the European Union, the following indicators were developed at the Geneva conference of 24 June 1994:

1. Maintenance and appropriate enhancement of forest resources and their contribution to global carbon cycles
2. Maintenance of forest ecosystem health and vitality
   2.1. Total amount of and, changes over the past 5 years in depositions of air pollutants (assessed in permanent plots)
   2.2. Changes in serious defoliation of forests using the UN/ECE and EU defoliation classification (classes 2, 3, and 4) over the past 5 years
      a. Serious damages caused by biotic or abiotic agents:
      b. severe damage caused by insects and diseases with a measurement of seriousness of the damage as a function of (mortality or) loss of growth
      c. annual area of burnt forest and other wooded land
      d. annual area affected by storm damage and volume harvested from these areas
      e. proportion of regeneration area seriously damaged by game and other animals or by grazing
      f. Changes in nutrient balance and acidity over the past 10 years (pH and CEC); level of saturation of CEC on the plots of the European network or of an equivalent national network
3. Maintenance and encouragement of productive functions of forests (wood and non-wood)
4. Maintenance, conservation and appropriate enhancement of biological diversity in forest ecosystems
5. Maintenance and appropriate enhancement of protective functions in forest management (notably soil and water)
6. Maintenance of other socio-economic functions and conditions.

4.4 A non-government approach: Forest Stewardship Council

The Forest Stewardship Council (FSC) is an international non-profit organisation, established following the 1992 'Earth Summit'. The group claims to promote the responsible management of the world's forests through market-based standard-setting and certification of forest products. Its standards are developed through consensus of its voluntary non-government members, with emphasis on environmental and social factors (deviating from the economistic focus of the Santiago Declaration's standard).

The Australian arm of the FSC, was established in 2001 and began development of its national standard in 2013 (FSC Australia 2019). The standard includes the following criteria for soil conservation:

- Vulnerable or high-risk soils are identified, including thin soils, soils with poor drainage and subject to water logging, and soils prone to compaction, erosion, instability and run-off
- Measures are implemented to reduce compaction, erosion and landslides
- Management activities maintain, enhance or restore soil stability and fertility. Fertility is to be maintained, enhanced or restored to natural levels or to levels that are ecologically advantageous for indigenous flora
- Chemicals and waste are not discharged into soil.

In terms of environmental values and impacts, the standard requires:

1. Mapping or other assessment of erosion risk
2. Mapping or other assessment of forest and other vegetation communities
3. Mapping or other assessment of significant species known or likely to occur in the Management Unit that may be negatively affected by management activities
4. Mapping or other assessment of important visual or landscape features
5. Relevant experts or consultation with knowledgeable stakeholders within and/or independent of The Organisation
6. Mapping or other assessment of soil type, erodibility and acid sulphate soils
7. Assessment of water resources and quality
8. An assessment of the adequacy and currency of Best Available Information for assessing environmental values and any further information that may need to be acquired.

The standard also makes a considerable number of recommendations in terms of acceptable forest management practices that should not degrade the ecosystem services provided by the forest.

The standard does not mandate or recommend specific measures by which to assess and monitor soil health and stability.

5 Australian adoption and modification

5.1 Policy framework

Australia's adoption of the Montréal Process was preceded by a variety of government inquiries, driven largely by public interest and concern into forest management (Howell *et al.* 2007). These culminated in the Intergovernmental Agreement on the Environment 1992, which divided roles and responsibilities for the environment between different levels of government, and the National Forest Policy Statement (NFPS) of the same year (Commonwealth of Australia 1992).

The NFPS was intended to "lay the foundation for forest management in Australia into the next century" and staked a claim for Australia being "a leading nation in developing sustainable forest management and practices." It mandated (subject to funding by individual jurisdictions) research and development in many areas, including integrated catchment management of land, water and vegetation resources in forests. The NFPS established principles for 'environmental care', including the protection of soil stability, soil, landscape and water catchment values through careful planning and regulation, based on sound science. It also commits Australia's governments to prepare a national 'state of the forests' review every five years.

In 1996, the Ministerial Council on Forestry, Fisheries and Agriculture agreed to adopt the Montréal Process as the basis for national assessment of forest management, in particular as part of the Regional Forest Agreement (RFA) process. This aimed to describe Commonwealth and State commitments and set up legally binding obligations for ecologically sustainable forest management at a regional level.

In 1997, a Montréal Process Implementation Group (MIG) was established to coordinate the development of an Australian set of criteria and indicators based on those from the Santiago Declaration. The MIG's development of a domestic indicator framework was based on the following principles for each indicator (Montréal Process Implementation Group 1998):

- Is it firmly linked to the criteria and relevant to the region and goals of forest management?
- Does it have a sound scientific or other relevant basis?
- Is it understandable and clearly interpretable?
- Is it sensitive and able to measure critical change with confidence?
- Are costs appropriate to its benefits (including noneconomic costs and benefits)?
- Is it feasible and realistic to measure over relevant timeframes and spatial scales?
- Is it capable of being measured against a standard or other performance measure where relevant?
- Will it contribute to continuous improvement in management and performance?

5.2 Criteria and indicators

5.2.1 Interim indicators

The framework of interim criteria and indicators developed by the Montréal Process Implementation Group in 1998 was endorsed by State and Territory government ministers and aimed to provide a framework that would allow assessment of progress towards achievement of sustainable forest management at a regional scale whilst also allowing aggregation to a national scale for reporting against the Montréal Process. As with the Santiago Declaration of 1995, 7 criteria were defined, of which the 4th (conservation and maintenance of soil and water resources) applied to soils. These interim indicators were:

- Area and percent of forest land systematically assessed for soil erosion hazard, and for which site-varying scientifically-based measures to protect soil and water values are implemented
- Area and percent of forest land (including plantations) managed primarily for protective functions, for example, watersheds, flood mitigation, landslide prevention and riparian zones
- Percent of stream kilometres in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation
- The total quantity of organic carbon in the forest floor (greater than 25 mm diameter components) and in the surface 30 cm of soil
- Proportion of harvested forest area with significant change in bulk density of any horizon of the surface (0–30 cm) soil
- Percent of water bodies in forest areas (e.g. stream kilometres, lake hectares) with significant change in biological diversity from the historic range of variability
- Percent of water bodies in forest areas—e.g. stream kilometres, lake hectares—with significant variance from the historic range of variability in pH, dissolved oxygen, levels of chemicals (electrical conductivity), sedimentation or temperature change
- Area and percent of forest land experiencing an accumulation of persistent toxic substances.

5.2.2 Finalised criteria and indicators

A revised framework of criteria and indicators was released by the Australian government in 2008 (Department of Agriculture, Fisheries and Forestry 2008).

As with the earlier interim indicators, soils are included under Criterion 4, however the indicators to support this criterion are reduced from the interim set and, as is immediately apparent, are considerably simplified:

4.1.a Area of forest land managed primarily for protective functions
4.1.b Management of the risk of soil erosion in forests
4.1.c Management of the risks to soil physical properties in forests
4.1.d Management of the risks to water quantity from forests
4.1.e Management of the risks to water quality in forests.

Of particular note is that these indicators are neither measurable nor assessable—they do not assess actual soil or water condition or health, and do not propose any measurable targets for what constitutes good management. Indeed, with the exception of indicator **4.1.a**, they bear little or no relation to either the Santiago Declaration indicators or the MIG's interim indicators. They are essentially 'meta-indicators' that allow for upward reporting and aggregation; however, with the exception of **4.1.a** they have no practical applicability for improvement of forest management processes.

Moreover, there are no indicators for soil chemical or biological properties, such as pH or organic matter. This is a significant departure from the Santiago Declaration, which explicitly refers to soil chemical properties in its indicator **4d**, and leaves Australian indicators open to ignoring key factors of soil degradation in forests (such as those identified in the studies in Section 6.6), ranging from bushfires to climate change.

5.2.3 Discussion

Australia's First Approximation Report to the MPWG noted that Australia lacked the capacity to report on a range of sustainable forest management indicators, particularly those regarding non-timber forest values (McDonald 1999), such as soil, because it was "not possible, practical or cost-effective" to do so (Montréal Process Liaison Office 2000). However, the need for further investigation and investment was clear, for as Stone *et al*. (2013) observed, without the implementation of a coordinated, systematic model for assessing forest health attributes, Australia would not be able to report on any of the MIG's interim indicators.

The revised indicators are less specific and measurable than the earlier interim indicators, and no longer meet the requirements of either the MIG's principles or the Santiago Declaration itself, arguably reducing incentive for such monitoring to be developed and implemented.

5.3 Applications in Australian forests

Turner and Pribble (1996) carried out a review into the applicability of the Santiago Declaration indicators to the Australian commercial forestry industry, in recognition of soil's key role in supporting forest ecosystems and biodiversity, and focused on soil erosion and stream ecosystem health, in particular water quality.

They concluded however, that numerous barriers to quantifying these indicators existed. This was particularly the case with indicator **4a**, (the area and percent of forest land with significant soil erosion) as they concluded that soil erosion from forested areas could not be assessed retrospectively, and regardless, there was no definition of what 'significant' soil erosion was. It is unclear what was the basis for this conclusion, as soil erosion was already a well-studied and quantified area by the time of the review, and advice on acceptable rates of soil erosion would have been available.

The review was more definitive in the case of **4b**, which was acknowledged as a useful measure of the sustainability of commercial forestry operations. Indicator **4c** was concluded to be difficult to apply without stream order mapping. Indicator **4d** required further study to assess the long-term impacts of logging on soil properties, but the study concluded that soil organic matter could be used as a surrogate for both physical and chemical properties that affect soil fertility.

Indicator **4e** likewise needed further research into the quantitative effects of soil physical disturbance on long-term growth. Likewise, the state of contemporary knowledge and data was insufficient to allow the water quality-related indicators (**4f** and **4g**) to be usefully applied.

Indicator **4h** was considered of little local concern as the deposition of industrial pollutants and damage caused by acid rain was not significant in the Australian environment. However, it was noted that this indicator should be monitored in areas of high risk, such as areas where pesticides, herbicides or organic waste was being applied. Forested areas around previously disturbed areas such as former mine sites could be considered as part of this category, (as could forested areas around current or former military facilities subject to potential contamination with PFAS/PFOS from firefighting foams.)

Subsequent work went further by developing and refining indicators of sustainable management for production forestry. Dignan *et al*. (1996) worked in the *Eucalyptus regnans* (mountain ash) forests in the Central Highlands of Victoria, which were subject of an experimental program investigating the application and effectiveness of clear-felling against other silvicultural systems. However, similar difficulties were encountered with the practical applications of the soil-related indicators, in both the lack of data and definitional difficulties such as what constituted 'significant' or 'tolerable' soil erosion.

The most quantitative indicators to emerge from Dignan *et al.* (1996) were that 'significantly diminished' soil organic matter amounted to a reduction of >15% from pre-harvest levels; and that 'significant compaction or change in soil physical properties' could be considered to be changes in bulk density of >15%, total porosity of >10% and aeration porosity of >20%.

Turner (1996) proceeded to apply the indicators identified in Turner and Pribble (1996) to *E. delegatensis* (alpine ash) commercial forests in the Bago/Maragle State Forests. However, the study concluded that there was insufficient data to assess any of the indicators, so instead proposed a set of alternatives. Most of these related to forest type, yield and regeneration, and included only estimates of soil erosion, movement or compaction.

Rab (1999) subsequently developed measures and standards for qualifying the 3 indicators of most relevance to soil—**4a**, **4d** and **4e**—in the forests of central Victoria. In terms of **4e**, sampling data from forest coupes in moderately steep to steep terrain with red and yellowish brown gradational soils included measurements of soils under different levels of disturbance. The measures studied were:

- Bulk density
- Aeration porosity
- Total porosity
- Saturated hydraulic conductivity (K_{sat}).

This data showed substantial change in all 4 measurements depending on the degree of disturbance. Indicator **4d** was assessed in the context of both timber harvesting and regeneration fire at the same sites and was measured by the organic matter content in the top 10 cm of soil. Indicator **4a** was assessed using percentage areas of topsoil and subsoil exposure combined with K_{sat} to produce an index of soil erosion potential. The actual rate of soil erosion could not be determined, though it was noted that previous studies suggested that soil erosion from logged areas was minimal after about 5 years, whereas erosion from snig tracks and roads could continue for 32 years or longer after harvesting.

Lacey *et al*. (2003) reported a number of studies that aimed to identify, provide and analyse data that would link soil change to growth impacts on individuals and stands (groups of trees). The study carried out 3 investigations in dry sclerophyll *Eucalyptus sieberi* (silvertop ash) forests in NSW, and 3 investigations in moist *E. regnans* (mountain ash) forests in Victoria. The NSW studies involved investigation of logging on soil physical properties, and tree regeneration and soil strength in a coupe logged 9 years before, both of which were located within Yambulla State Forest in the far south-east of the state. One of the Victoria studies analysed factors influencing the extent of soil disturbance in 20 clear-felled coupes, whilst a second examined soil physical properties and response of regrowth to soil disturbance in a coupe logged 10 years before, and a third involved comparison of different survey methods for recording soil disturbance, soil sampling and assessing change against what was then interim soil physical indicator **4.1.e**.

The NSW studies indicated that:

- soil strength increased significantly in areas subject to traffic (roads, snig tracks and snig landings), and this significantly limited regenerative growth in these areas

- overall change in soil physical properties in logged areas was low, and any increase in bulk density in the nominated depth range under interim indicator **4.1.e** almost never exceeded the threshold of significance (20%).

The study also noted, however, that the number of results exceeding the threshold increased substantially if bulk density was assessed within the top 10 cm of soil.

The Victorian studies indicated:

- a strong relationship between volume of timber extracted and degree and extent of soil profile disturbance
- snig tracks and other areas disturbed to subsoil levels had significantly higher bulk density and lower organic matter and porosity than undisturbed areas
- estimates of disturbance class were not significantly influenced by sample size, suggesting that lesser sample size may be adequate.

Lacey *et al.* (2003) recommended that indicator **4.1.e** should be assessed over time based on simple mapping of disturbance classes, with interpretation based on scientifically established relationships between disturbance class, soil type and logging conditions (e.g. soil moisture content at time of harvest), and reported as the area and percent of the net logged area occupied by detrimental disturbance. Further, it recommended that at least 20% of harvested coupes should be selected and assessed in this manner. Since the study showed a clear influence of soil disturbance on regeneration vigour and, ultimately, timber volumes, soil disturbance needs to be considered by forest managers, and further research should continue.

The Eucalyptus regnans *(mountain ash) forests of Victoria's Central Highlands have been a focus of studies into soil health of Australian forests. Photo: Parks Victoria.*

5.4 Australian State of the Forests reporting

Since 1998 Australia has reported every 5 years on the Montréal Process indicators in its *State of the Forests Report*. This is produced by the Montréal Process Implementation Group for Australia (MIG) on behalf of the Australian, state and territory governments, using information supplied by those governments. The latest report was produced in 2018 (Montréal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018).

The reports track Australia's progress against the MIG's revised set of 44 indicators (Department of Agriculture, Forestry and Fisheries 2008). As noted in Section 5.2 above, these indicators do not impose any measurable targets for sustainable soil management in forests and provide no information on what the state of forest soils is or its trajectory. It is also not at all clear what actual measures or data are used to make these assessments, beyond reference to a few case studies. Indeed, as Read and Howell (2019) noted, whilst spatial analysis techniques for mapping forest types and tenures have significantly improved, quantitative data for some forest attributes remain "incomplete or experimental", including those involving ecosystem services such as soil. The inadequacy of this approach is demonstrated by the fact that even the measurement of areas assessed for risk of soil erosion and risk to soil physical properties in the 2018 *State of the Forests Report* are blank for all jurisdictions apart from NSW and the ACT.

Thus, beyond providing basic and incomplete statistics of areas subject to various levels of assessment, the current *State of the Forests Report* process does not provide a viable foundation for the assessment of Australian compliance with the provisions of the Montréal Process, and its lack of fundamental data, particularly in the area of landscapes and soils, reflects both the lack of systematic data collection by the states and territories and the lack of specificity and applicability of the revised indicators. This is the case even for Victoria with its systematic forest monitoring program (see Section 5.5 below).

There was an attempt to introduce such a systematic scheme at a national level, the Continental Forest Monitoring Program (CFMP)—see Section 6.5.2—but this was never implemented.

5.5 Tasmania

Tasmania's *Forest Practices Act 1985* mandated the development and enforcement of a Forest Practices Code, which was first published in 1987. This is the only forest code in Australia and one of few in the world to apply to both private and public lands (Forest Practices Authority 2019). Its objective is to "achieve sustainable management of Crown and private forests with due care for the environment and taking into account social, economic and environmental outcomes while delivering… practical standards for forest management, timber harvesting and other forest operations…" (Forest Practices Authority 2015).

The Code is comprehensive and prescribes "the manner in which forest practices are to be conducted so as to provide reasonable protection to the environment" (Forest Practices Authority 2015). It includes a requirement for monitoring and reporting of the implementation and effectiveness of forest practices, as part of Forest Practices Plans that are prepared in accordance with the Code by Forest Practices Officers employed by Sustainable Timber Tasmania. The Code recognises that proper care of forest soils is fundamental to sustainable forestry and includes provisions for:

- the avoidance of roading into areas subject to slope instability, construction in dry season only and minimisation of soil exposure, with special provisions required in areas of high soil erodibility by both water and wind

- use of appropriate machinery to limit impact of harvesting on soils (e.g. through reduced static ground pressure), avoidance of machinery use on saturated soils and minimisation of the number of snig tracks
- control and prevention of unacceptable levels of soil erosion, nutrient loss and mass movements, and of excessive compaction, puddling and mixing of topsoils and subsoils
- prescription of slopes and soil erodibility classes at which cultivation is unacceptable during forest re-establishment.

Note that the Code does not actually define what the terms 'reasonable' or 'unacceptable' mean—e.g. it does not provide a rate of soil loss (t/ha/year) that is considered unacceptable—nor does it provide any information about what monitoring and evaluation processes under Forest Protection Plans is required. It is also not backed by any systematic monitoring program that would, for example, allow Tasmania to assess the state of its forest soils and determine whether the provisions of the Forest Protection Plans were effective in their protection.

5.6 Victoria

In 2007 the state of Victoria went the furthest of any Australian jurisdiction towards implementing the substance of the Santiago Declaration when it released its *Criteria and Indicators for Sustainable Forest Management in Victoria* (Department of Sustainability and Environment 2007), which met the requirements of Victoria's *Sustainable Forests (Timber) Act 2004* as well as being consistent with the MIG criteria and indicators.

Under the *SF(T) Act*, Victoria is required to produce a *State of the Forests* report every 5 years. The latest report (Commissioner for Environmental Sustainability Victoria 2018) describes the results of the Forest Audit Program, which is intended to provide an independent, objective assessment of VicForests' level of compliance with environmental regulations for timber production in state forests.

In turn this program is supported by the Victorian Forest Monitoring Program (VFMP), which has established a network of permanent monitoring sites backed up by interpretation of aerial photographic and satellite imagery. Establishment of this program is described by Haywood *et al.* (2017). Its purpose is to "assess and monitor the extent, state and sustainable development of Victoria's public forests in a timely and accurate manner."

This program is described in more detail in Section 6.6.

5.7 Western Australia

The *Forest Management Plan 2004–2013* (Conservation Commission of Western Australia 2004) included provisions for protection of soil and water resources that were developed during the years of its implementation. The follow-on *Forest Management Plan 2014–2023* (Conservation Commission of Western Australia 2014) continues the focus on reducing soil erosion by minimising vehicle movements associated with timber harvesting, using only appropriate vehicles, and trafficking soils under appropriate soil moisture conditions.

Part 4 of the related manual of procedures (Department of Environment and Conservation 2007) relates to protecting soil values. These are measured by a stratified random sample of harvest cells every year, with soil damage not to exceed prescribed maximum levels for 95% of cells surveyed, except where prescribed levels cannot be achieved with the application of good harvest practices. Field assessment of soil damage includes a visual assessment of topsoil removed, mixed, compacted and undamaged along 4 sample lines within a 100 × 100 m plot in the most affected part of each felling block.

Though there are specified limits for soil erosion, there appears to be no requirement for this information to be scientifically collected and recorded as part of any monitoring process, nor is there a requirement to revisit a disturbed site to monitor further change over time. The most recent national *State of the Forests Report* (Montréal Process Implementation Group for Australia and National Forest Inventory Steering Committee 2018) indicates that no data has been recorded in WA against the MIG targets for soil management.

5.8 New South Wales

NSW has a variety of legally binding instruments that address the risk of soil erosion in both native forests and plantations. These instruments have varying levels of compliance with the Montréal Process indicators—whilst multiple-use public forests and plantations are required to take into account rainfall intensity, slope, soil erodibility and management practices that result in soil disturbance, and all forms of erosion, the same is not wholly true for other tenures such as public nature conservation reserves and leasehold land; and requirements to maintain soil physical properties and compliance with prescribed mitigation measures to minimise impacts on soils are not complete.

A few years after the Santiago Declaration, NSW developed its four-class Soil Regolith Stability Classification (Murphy *et al*. 1998), which though unconnected with the Montréal Process can be considered as a basic assessment of baseline forest soil condition, albeit for a specific purpose. Soil regolith classes were mapped in the eastern part of the state as an input to the soil erosion and water pollution hazard assessment of forestry operations under NSW State Forests' pollution control licence. Subsequently the soil regolith mapping has been used as part of NSW's Integrated Forestry Operation Approvals (IFOA) process, which sets requirements for forestry operations on State forests and Crown timber lands in NSW.

This classification aimed to overcome the variable utility of the RUSLE soil erodibility factor (K factor) in forested environments by providing a classification of soils' susceptibility to erosion based on experience and knowledge of soil behaviour. The classification includes both soil coherence and sediment delivery potential, and thus addresses, if indirectly, somewhat more than the strictly soil-based indicators (**4a**, **4d** and **4e**) defined under the Santiago Declaration, at least in terms of sediment-generating capability.

Data used to generate the final soil regolith stability class for each map unit (soil landscape) included:

- Soil texture
- Coarse fragments
- Aggregate stability
- Soil structure
- Dispersion percentage
- Soil depth
- Soil colour
- Soil drainage
- Existing erosion.

These data were analysed through expert interpretation rather than through arithmetic or statistical analysis or modelling. Where soil information was not available, parent material was used as a surrogate.

This scheme provides a basis for further detailed site-based assessment and monitoring. However, as it is based on assessments of fundamental soil characteristics and does not include assessment or quantification of specific measures or change over time, the Soil Regolith Stability Classification is not a soil health measurement and monitoring methodology. However, it shows the benefits of a simple but effective index to inform planning and management of soils and erosion control in forestry.

Soil disturbance during and after forest harvesting can be considerable, as in this Pinus radiata *(radiata pine) plantation south of Bathurst, NSW. Photo: H Milford.*

6 Quantifying forest and soil health

6.1 Worldwide

The UN FAO's soil health indicator scheme (referred to in Section 2.3) comprises 7 soil qualities, each of which is based on a number of soil measures:

- Nutrient availability
  - Texture
  - Structure
  - Organic C
  - pH
  - Total Exchangeable Bases
- Nutrient retention capacity
  - Organic C
  - Texture
  - Base Saturation
  - Cation Exchange Capacity
  - Cation Exchange Capacity, clay fraction
  - pH (indicator for Al toxicity and micronutrient deficiencies).
- Rooting conditions
  - Depth
  - Texture
  - Structure
  - Vertic, Gelic or Petric properties
  - Presence of coarse fragments
- Oxygen availability to roots
  - FAO 74 soil phases: phreatic
  - FAO 90 soil phases: phreatic, anthraquic, inundic and placic.
- Excess salts
  - Electrical conductivity
  - Exchangeable Sodium Percentage
- Toxicity
  - Calcium carbonate
  - Gypsum
  - Petrocalcic or petrogypsic properties
- Workability
  - Soil depth
  - Stony or rocky soils
  - FAO 74 soil phases: stony, lithic, petric, petrocalcic, petroferric, fragipan and duripan
  - FAO 90 soil phases: lithic, petroferric, rudic, skeletic, duripan and fragipan.

As noted, these measures are of most relevance for production agriculture, although at least some are applicable to forested environments.

More recent developments have included the development of a global soil health database known as SoilHealthDB (Jian *et al.* 2020). This database integrates data harvested from 321 existing studies, comprising some 5,907 comparisons from 354 geographic sites in 42 countries (including some from Australia), and includes 42 soil health indicators and 46 background indicators describing factors such as soil type, elevation and climate. So far, the database has focused on 4 management areas: cover crops, no-tillage, agro-forestry and organic farming. Soil indicators include the following, though these data are not available for all locations—in which case they are estimated:

- Bulk density
- Soil organic C (%)
- Soil mineralizable C
- Soil organic C stock (Mg/ha)
- Soil organic carbon sequestration rate (Mg/ha/cm/yr; calculated)
- Total N
- Soil mineralizable N
- Soil N_2O efflux
- Total P
- CEC and exchangeable K
- Microelements (Mn, Zn, Cu etc.)
- Base saturation
- pH
- EC
- Soil aggregation
- Soil porosity
- Soil penetration resistance
- Soil infiltration rate
- Saturated hydraulic conductivity (K_{sat})
- Available water-holding capacity
- Soil erosion
- Wind erosion
- Runoff
- Soil nutrient leaching
- Soil fauna
- Soil fungi
- Soil microbial activity
- Substrate-induced respiration
- CO2 burst test respiration
- CO2 efflux
- CH4 emission
- Microbe biomass C
- Microbe biomass N
- World Reference Base soil classification
- Soil Quality Index

6.2 United States of America

The Forest Service of the United States Department of Agriculture (USDA) instituted its Forest Inventory and Analysis (FIA) program in 1930, and soil analysis has been part of this program for some considerable time.

The Forest Health Monitoring (FHM) Program was initiated in 1990 to provide precise, accurate statistical information on changes to the ~304 million ha of forested land in the USA. This program applies to all forested land in the USA regardless of ownership or availability for harvesting and is backed by federally-legislated financial support and formal federal-state partnership agreements.

The Integrated Monitoring Framework (IMF) supports this program and its hierarchical monitoring framework is described in Figure 4 (below).

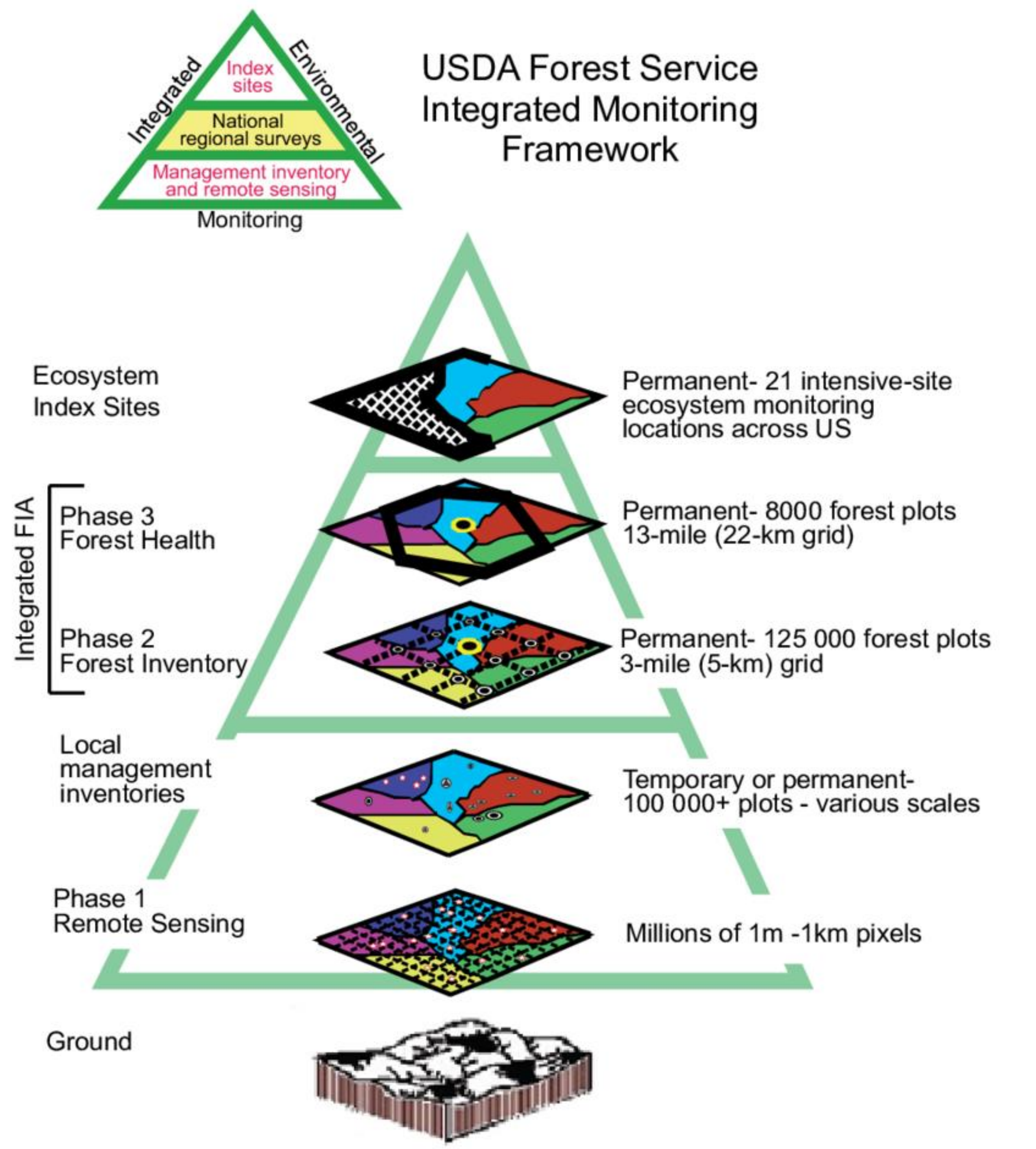


Figure 4 A diagrammatic representation of the USDA Forest Service's integrated monitoring framework (from Bennett and Tkacz 2008).

The FHM program carries out forest monitoring on the basis of 3 'phases'—the first being remotely-sensed data, the second being one field site per 6,000 acre (2,428 ha) hexagonal area of forest, and the third being a subset of 'phase 2' sites that are more intensively studied, including soil attributes (USDA Forest Service 2005a). For forest health monitoring, about 8,000 'phase 3' plots representing about 38,850 ha of forested land are involved, each of which is measured once every 5-10 years (Bennett and Tkacz 2008). Results are reported annually.

Each 'phase 3' plot site is permanently located and consists of 4 circular subplots in a fixed pattern. Sampling design is described in one of the many factsheets that support the program (USDA Forest Service 2005b), whilst another describes the analyses carried out. For the purpose of soil condition monitoring, 2 samples of mineral soil are collected at fixed depths of 0–10 cm and 10–20 cm. Analysis includes the following variables:

- Bulk density
- Water content
- Coarse fragment (>2 mm) content
- pH (water and 0.01M $CaCl_2$)
- Total C
- Total organic C
- Total inorganic C (carbonates) [only in soils where pH >7.5]
- Total N
- Exchangeable cations (Al, Ca, K, Mg, Mn, Na)
- Exchangeable S
- Trace metals (Ba, Cd, Cu, Mn, Ni, Pb, Sr, Zn)
- Extractable P (Bray 1 for soils where pH <6, Olsen for soils where pH >6)

For forest floor and litter (3 samples per plot), the analyses are:

- Bulk density
- Water content
- Total C
- Total N.

The concept of soil quality was further integrated into the FIA program when Amacher *et al.* (2007) developed a Soil Quality Index (SQI) for forest monitoring and management. This is described in more detail in Section 7.3.

Lawrence *et al.* (2016) provided an up-to-date view of the design and implementation of a soil monitoring program in forest soils, in the light of recent research showing that important chemical soil characteristics can vary significantly in less than a decade in response to environmental changes—e.g. acid rain. Their procedure has been developed to support the ongoing monitoring of soil condition in the forested uplands of the north-eastern USA and south-eastern Canada.

In particular, Lawrence *et al*. (2016) addressed the problems of accurately resampling soils given their spatial variability (in all 3 dimensions) and the inevitably destructive methods of sample collection; and they provide methods of sampling aimed at minimising measurement instability. The procedure involves the establishment of study units based on landscape type, dividing each unit into 25 equally sized plots, and randomly selecting a chosen number of plots for each 5-year repeat observation, a period that may be adjusted according to the expected rate of change of the variables to be measured.

Methods of soil description and sampling are recommended, using full soil descriptions and sampling by soil layer/horizon wherever possible, and the paper also demonstrates methods of combining soil resampling results from programs with differing designs so as to produce larger regional datasets. Lawrence *et al*. (2016) further recommended maintenance of a sample archive for future re-analysis, not only to avoid analytical bias but also to answer new questions beyond those originally posed when the system was set up.

The paper does not specifically recommend measures for forest soil monitoring, with this requirement to be dealt with in the context of the specific needs for a monitoring program.

6.3 United Kingdom

Great Britain implemented the guidelines from the Helsinki Process as part of pan-European criteria and indicators for sustainable forest management, and the monitoring programs that support them, albeit with some modification to suit British conditions. Indicators include maintenance of forest ecosystem health and vitality, under which changes in nutrient balance (CEC) and are analysed over 10-year timeframes and monitoring of soil compaction and soil erosion are promoted.

Sixty-seven 'Level I' plots are sampled and analysed every 10-20 years, whilst 10 intensive 'Level II' sites are monitored for solid soil chemistry every 10 years, and solution chemistry every 2 weeks. Procedures used are as documented by the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests, ICP Forests (Cools and De Vos 2016).

Each site is described in detail and classified using the World Reference Base for Soil Resources. Samples are taken both of individual soil layers and at fixed depths (at least: organic layer; 0-10 cm; 10-20 cm; 20-40 cm; and (for Level II sites) 40-80 cm), and key soil parameters are:

- Total C
- Total N
- Nutrients (Ca, K, Mg, Mn, P)
- pH
- Carbonates
- Exchangeable cations
- Exchangeable acidity
- Heavy metals (Cd, Cu, Cr, Hg, Ni, Pb, Zn)
- Particle size distribution and soil texture
- Organic layer mass (organic stocks)
- Bulk density (fine earth)
- Coarse fragment content
- Soil Water Retention Characteristic (SWRC).

6.4 New Zealand

Sparling and Schipper (2002) documents New Zealand's policy approach to the soil quality issue, and the scientific response. New Zealand relies heavily on the economic contribution of agriculture and forestry. After radically deregulating and unsubsidising its economy and farming sector in the 1990s, the country had to develop a new environmental policy framework.

In requiring monitoring of the environment without mandating any ways of doing so, the *Resource Management Act 1991* required a considerable increase in soil quality research in the country. These investigations delivered the design for a monitoring program, a set of standardised sampling methods and selection of 9 soil properties for soil quality assessment, to be implemented by New Zealand's 12 regional councils:

- Total C
- Total N
- Mineralisable N
- pH
- Olsen P
- Bulk density
- Macroporosity

- Exchangeable cations
- Aggregate stability.

Principle Component Analysis allowed individual indicators to be combined into 4 primary factors:

- Olsen P
- pH
- Aerobic N, total C, total N
- Bulk density, macroporosity.

By 2001, 511 monitoring sites had been established, representing ~98% of the country's land area. Subsequently a guide for land and soil monitoring was prepared (Land Monitoring Forum 2009) to support regional councils in their State of Environment reporting responsibilities under the *RMA Act*, including the establishment and monitoring of further sites.

The procedure for soil quality health monitoring recommends different resampling frequencies depending on land use (for plantation forestry, 5–10 years, and for indigenous vegetation 10–20 years) applied to well over 50 sites in each council area. Each site is characterised by a soil profile description to >1 m depth (where possible) and is usually sampled along a 50 m transect, laid out following the landscape contour, at 2 m intervals. Each of the 25 cores is taken to 10 cm depth of mineral soil, bulked, then laboratory-tested. Three (3) intact cores for bulk density testing, and spade samples for aggregate stability testing, are collected at 15 m, 30 m and 45 m positions along the transect.

6.5 Australia

6.5.1 Current situation

In comparison to these more or less structured, systematic national or international monitoring operations, Australian assessment and monitoring of forests and/or soils has tended to be rather fragmentary, unstructured and unsystematic.

In many ways this is reflective of the "dysfunctional system of Australian federalism" (Williams 2015): natural resource management is generally the constitutional responsibility of individual states and territories, who have proceeded in their own ways to legislate and enforce (or not) controls on soil conservation and sustainable natural resource management. In contrast to other nations such as the USA, where behavioural change has been enforced where required, Australian governments have focused on extension, awareness and education rather than regulation (Williams 2015).

Until recently, there has also been no standard set of indicators for monitoring soil condition in Australia, and limited enforcement mechanisms to ensure individual states and other agencies adopt the standards that are proposed. Furthermore, individual states have typically committed limited and episodic resources to the area, with similarly discontinuous injections of resources from the Federal level; and since monitoring requires consistent long-term effort, it is not surprising that very little coherent monitoring of soils has been achieved in most jurisdictions.

The most intensive and systematic effort has come in Victoria with its Victorian Forest Monitoring Program, VFMP (see Section 6.5.4), though this itself has significant limitations in providing information of practical use for forest management. A national system, the Continental Forest Monitoring Framework, CFMF (see Section 6.5.2 below) informed the development of the VFMP but was never implemented.

NSW's situation is reviewed separately in Section 6.6.

6.5.2 Continental Forest Monitoring Framework

An attempt to generate momentum towards a national assessment of forests came through a consortium of State and Federal Government agencies, the National Forest Inventory, in 1998. A conceptual monitoring framework was refined over succeeding years and was published in 2006 (Wood *et al*. 2006) as the Continental Forest Monitoring Framework (CFMF). A network of permanent monitoring sites was proposed across tenures and native forest types, with repeat observations every 5 years, backed by a range of remotely sensed imagery (see Figure 5 below), similar to the hierarchical approach used by the USA's Forest Health Monitoring program (see Section 6.2).

To inform the proposal, a pilot study was carried out in cooperation between the Federal and Victorian Governments in north-east Victoria, involving 45 'image plots' classified using SPOT imagery and LiDAR, and 23 field plots of 30 × 30 m area on a systematic grid at which attributes including soil bulk density and C were measured.

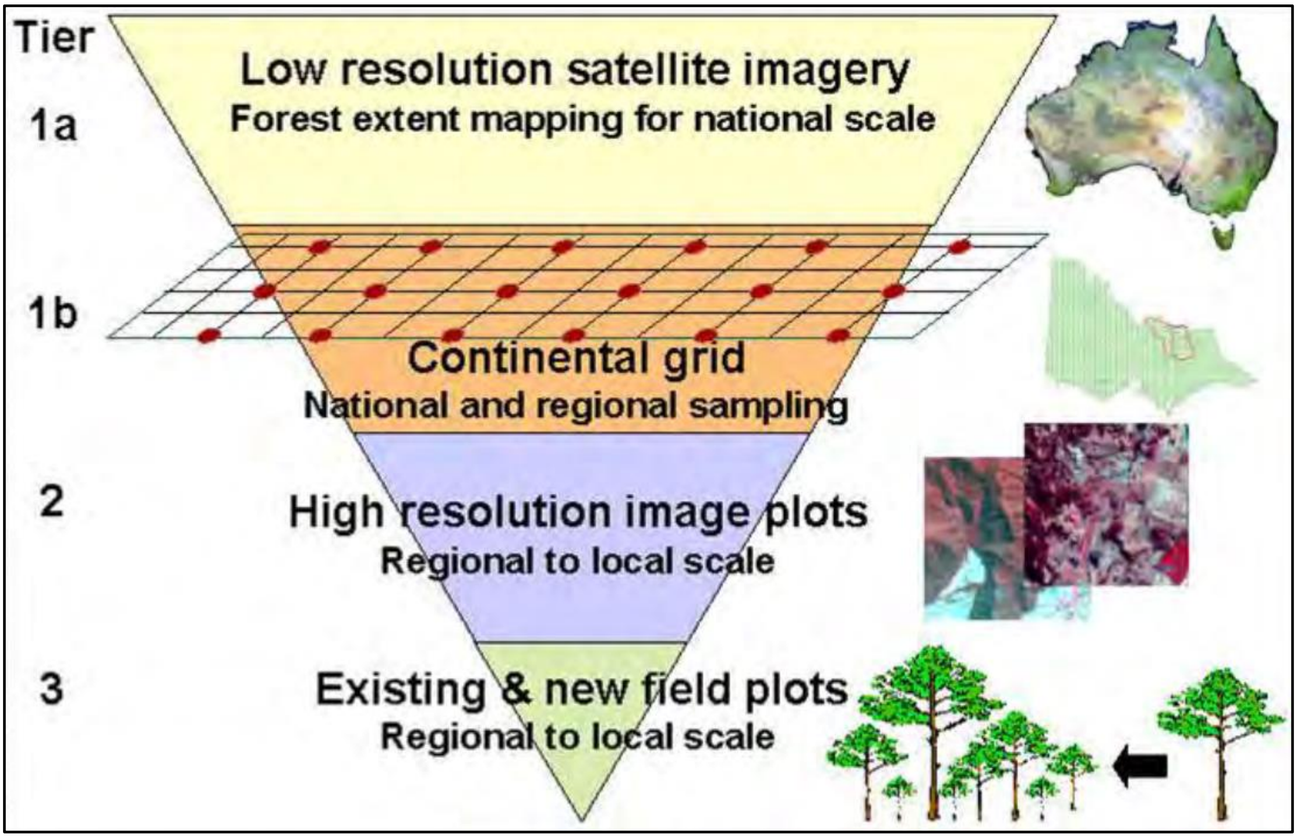


Figure 5 Multi-tier design of the Continental Forest Monitoring Framework

The pilot proved the validity of the approach, however the scale of the investment in rolling out a nationwide CFMF perhaps proved too great—at a sampling density of 20 km, over 16,200 Tier 1b image plots would be required, along with over 2,800 Tier 3 field plots, requiring an initial investment of A$4.45 million per annum for the first 5 years, falling to $2.35m per annum in subsequent years. The study noted that implementing a system similar to the USA's would cost approximately A$40m per annum, or one similar to New Zealand's for A$15m per annum, and so the CFMF could be considered something of a bargain, but nonetheless the CFMF was not funded and remains unimplemented, though it did inform Victoria's development of its own forest monitoring program (see Section 6.5.4).

Nationwide monitoring of forest condition has since been resurrected, though in a less systematic way, under Australia's Terrestrial Ecosystem Research Network (TERN, see Section 6.8).

6.5.3 Monitoring soil change: Principles and practices for Australia conditions

Another national approach was proposed by the soil and landscape scientific community in the 2000s as part of the National Land and Water Resources Audit (NLWRA) in a comprehensive report entitled *Monitoring Soil Change: Principles and practices for Australian conditions* (McKenzie *et al*. 2002). This 'blueprint for monitoring soil change in Australia' provided a description of the needs for monitoring soil change in the context of knowledge of the natural landscape and the study of both natural and modified ecosystems, including long-term ecological research. The overall aim was addressing the 'matters for target' proposed by the National Natural Resource Management Monitoring and Evaluation Framework, one of which was soil condition. The 4 indicators endorsed by the Audit Advisory Council in December 2007 under this 'matter for target' were:

- Soil acidification
- Soil carbon
- Water erosion
- Wind erosion.

In the context of the known or expected variability of soil properties in natural landscapes, the report proposed the setting up of monitoring sites of 25 × 25 m area, divided into subplots of 5 × 5 m for stratified random sampling, with profiles characterised on establishment, ideally with a pit observation to at least 1 m depth where possible, and ongoing monitoring of a smaller set of variables on a regular basis, with monitoring also undertaken using surrogates such as aerial photography and remote sensing. At a minimum, each site required characterisation for the following attributes:

- Basic landscape features as per McDonald *et al.* (1990)
- Australian Soil Classification (ASC) to Great Group level
- Soil texture
- Soil colour
- Soil structure
- Coarse fragment volume (%)
- Segregations (type and proportion)
- pH (CaCl2 and water)
- Organic C
- Exchangeable cations and CEC
- Electrical conductivity
- Particle size distribution
- Bulk density
- Water retention
- Hydraulic conductivity
- Aggregate stability

Soil sampling was to be performed according to soil layers, and a portion of each sample set aside in an archive for long-term storage.

Land and Water Australia, the NLWRA's parent organisation, was defunded in 2009, and their proposal was not widely applied, though it did inform some state-based monitoring—e.g. NSW's monitoring, evaluation and reporting (MER) program for soils (see Section 6.6.3). A national approach is again being proposed through the TERN cooperative research program (see Section 6.8), which fulfils at least some of the aims of the earlier proposal.

6.5.4 Victorian Forest Monitoring Program

The Victorian Forest Monitoring Program (VFMP) has established a network of permanent monitoring sites backed up by interpretation of aerial photographic and satellite imagery. Establishment of this program is described by Haywood *et al*. (2017). Its purpose is to "assess and monitor the extent, state and sustainable development of Victoria's public forests in a timely and accurate manner."

The design of the VFMP was heavily influenced by the work done earlier on the Continental Forest Monitoring Framework (see Section 6.5.2 above). The VFMP was initiated in 2010 with a pilot program in East Gippsland, and now comprises 859 monitoring plots laid out in grid form across Victoria's various Crown land tenures—see Figure 5 (above)—mainly state forests but also national parks and other conservation reserves. The project has been referred to as "Australia's most comprehensive statewide public forest monitoring program, that is consistent with best practice elsewhere in the OECD countries" (DELWP 2015). Establishment of the plot network was based on systematic stratified sampling using Interim Biogeographic Regionalisation for Australia (IBRA) bioregions combined with Crown land category, together creating a sampling grid of between 2–20 km that produced a sample size of about 30 per stratum. The 5-year re-measurement cycle of the ground plots commenced in 2015.

Each site is a circle 11.28 m in diameter (the 'Large Tree Plot'), within which are located 12 1 × 1 m square peripheral 'Vegetation Quadrats' (arranged like the hours on a clock face) and an inner circular area (the 'Small Tree Plot'). At the centre of each plot is located a pair of soil pits. Measurement of plots is carried out by commercial contractors under tender using standards set out in the VFMP's Standard Operating Procedures (DELWP 2017).

The 30 priority indicators that are monitored under the VFMP were formulated through a workshop in 2011, and implementation was guided by a scientific advisory panel consisting of 3 experts in the field of large-scale forest monitoring. Apart from a description of the soil, the only soil-related measure is C content (Haywood *et al*. 2017), and soil sampling under the Program has been temporarily suspended since 2013 pending development of a suitable and efficient sampling protocol (DELWP 2017).

Under the Criteria and Indicators for Victoria (Department of Sustainability and Environment 2007), there is a single soil-related indicator—"area and percentage of forest by activity type systematically assessed for risk to soil attributes". Note that this 'indicator' refers only to the act of assessment—it does not indicate what the soil condition is, according to what measures, or whether it is improving or degrading. This indicator is therefore of little use in assessing the sustainability of forest soil management.

Likewise, the success of the VFMP appears to be mixed. Assessment against this indicator through the *Victorian State of the Forests Report 2018* (Commissioner for Environmental Sustainability Victoria 2018) does not appear to be informed by VFMP data and refers only to the results of independent auditing compliance for harvesting and roading requirements carried out over 34 coupes in Victorian state forests. Likewise, Victoria's reporting of progress on implementation of its Regional Forest Agreements (DELWP 2019) appears to make no use of VFMP data, but instead relies on modelling forest, pasture and bare earth scenarios. No information about the actual condition or management of Victorian forest lands and soils is included.

In terms of reporting, the Victorian State of the Forests reports assess only the single measurable indicator under the *Criteria and Indicators for Victoria*—i.e. they assess the area and percentage of forest systematically assessed for risk to soil attributes, but not what those risks are, their severity or their trajectory.

Therefore, in not providing any indication of either baseline soil condition or change over time, the Victorian process does not provide useful information to guide forest soil management or protection, and its aim of providing input to land management policy and decision-making has not been achieved. In acknowledging this, the *Victorian State of the Forests Report 2018* notes that limitations to the VFMP, in particular its low sample size, makes its application to finer scale or discrete measurement not recommended, that increasing the sample size has had the unwanted side-effect of introducing more analytical noise to the data, and that more accurate trend analysis awaits collection of the full second cycle of measurement. It concludes that the VFMP is best suited to broad-scale, long-term trends in forest health and condition, and needs continuous improvement to remain a useful tool for monitoring the effect of land management interventions.

The experience of the VFMP therefore provides some lessons from which NSW can learn for its implementation of a forest soil monitoring program. In particular, the data gathered must identify issues in a way that is relevant to, and sufficiently timely and accurate for, improvements in forest management planning and implementation.

6.6 New South Wales

6.6.1 Forests

The Forestry Corporation of NSW monitors operational implementation of, and compliance with, soil conservation (and water quality) measures as part of its Forest Management Plans (pursuant to the IFOAs, see Section 5.8). However, with the exception of its research sites (such as that in the Karuah State Forest north of Newcastle) it does not report monitoring of the condition, health or stability of forest soils in either undisturbed, logged or fire-affected landscapes.

6.6.2 Targets, criteria and indicators

In 2003 the NSW Government enacted the *Natural Resources Commission Act*, which established the Natural Resources Commission (NRC). Its function is to provide the government with independent advice on natural resource management, including carrying out major assessments, auditing state and local strategic plans, and setting of targets and standards and auditing compliance. In 2005 the NRC released state-wide standards and targets for natural resource management (NRC 2005), which included 2 targets for land and soil:

- By 2015 there is an improvement in soil condition
- By 2015 there is an increase in the area of land managed within its capability.

An investigation as to whether these targets had been met was undertaken as part of the *NSW Monitoring, Evaluation and Reporting Strategy 2010–2015* (see Section 6.6.3 below).

In 2012 the NRC recommended the replacement of the 21 targets from 2005 with a single goal and 5 much broader targets, which include a single soil-related target:

Improve soil condition.

The NRC's initiative (2012) contains several aims that monitoring of soil condition should achieve:

- measuring the performance of NRM management actions at state and regional scales with regard to securing improvements in the condition of natural resources and evaluating return on investment
- maintaining an adequate core set of long-term datasets to detect and evaluate the condition of and change over time in soil, for example organic carbon and soil structure (which are existing datasets under the current program)
- appropriately securing those datasets and making them available to natural resource managers and the community on demand
- developing and improving models and forecasting frameworks (for example models for wind and sheet erosion) to support decision making, and targeting data collection programs to verify modelling predictions
- using ancillary datasets from other programs—such as those established to meet agency statutory functions, for example the *Soil Conservation Act 1938* (NSW)—to help evaluate progress developing and implementing information management and methodological standards and protocols
- implementing collaborative monitoring, evaluation and reporting programs initiatives with CMAs to support the implementation of whole-of-government and community catchment action plans.

As yet there has been no program, in forests or in other NSW environments, to address these aims. The *NRC soil health and stability monitoring in forests* project provides an opportunity to put these ideas into practice.

In terms of NSW's production forest lands, under the RFA process the NSW Government established a framework for sustainable management of forested lands. In 2016 the NSW Environmental Protection Agency (EPA) released its *Ecologically Sustainable Forest Management (ESFM) Criteria and Indicators* for regions covered by NSW Forest Agreements (EPA 2016). These are substantially the same as the revised indicators delivered by the MIG but are refined in some areas to be more regionally specific. The EPA has consolidated the ESFM indicators to give a total of 36, of which 2 directly relate to soils. These are:

- Area of forest land managed primarily for protective functions
- Management of the risk of soil erosion in forests
- Management of the risks to soil physical properties in forests.

Being identical to the MIG's revised soil indicators, these indicators require no collection or analysis of specific data and set no measures by which they can be assessed.

6.6.3 Monitoring, Evaluation and Reporting

The NSW Government's most intensive effort to monitor soils came under the *NSW Monitoring, Evaluation and Reporting Strategy 2010–2015,* which aimed to monitor and evaluate soil condition against the land and soil targets set by the NSW Natural Resource Commission in 2005.

One part of the project delivered a statewide coverage of land and soil capability against which to assess the targets. The other, monitoring component was intended to assess soil condition under different forms of land management against that capability (Chapman *et al.* 2011).

Monitoring sites were established within what were described as priority soil monitoring units (SMUs), which were large tracts of land with the following characteristics:

- contain soils that occur either homogenously or in repeatable patterns
- occupy significant areas
- have soil conditions that are vulnerable to change
- are important in terms of productivity or ability to provide ecosystem services.

The selected SMUs covered about 35% of the land area of NSW. It was intended that around 1,300 sites would be required to characterise them, however only 866 were established, of which 777 sites had sufficient data to be used for analysis and 661 could be used for the assessment of land management against capability. 189 of these sites were located within forests or woodlands.

A small number of sites established under the NSW Monitoring, Evaluation and Reporting Strategy were located in forest environments. Photo: OEH.

Each site consisted of a 25m x 25m quadrate. Where possible, sites were paired on the same soil type but across different land uses, including undisturbed reference sites where the soil was considered to be in an undisturbed pre-European natural state. The indicators used were:

- sheet erosion
- gully erosion
- wind erosion
- acidity
- organic carbon
- soil structure
- salinity
- acid sulfate soils.

To assess these indicators, the measures used were:

- pH ($CaCl_2$)
- pH buffering capacity (for samples with an upper depth of >10 cm)
- Total organic C
- Bulk density
- Electrical conductivity
- Texture (particle size analysis and USCS)
- Dispersion percentage
- Aggregate stability
- Cation exchange capacity and exchangeable Al, Ca, K, Mg, Na
- Total Fe (only for suspected Ferrosols)
- Total P
- P sorption
- Wind-erodible aggregates
- Water repellence.

Key indicators were evaluated against a reference condition. The more an indicator had deteriorated relative to the reference, the poorer the condition. The program assigned soil condition index classes to present an estimation of overall combined soil condition. Statewide results from this program against the NRC targets were presented in OEH (2014).

Sites were intended to be revisited on 5-year intervals. Some sites have been revisited for soil C monitoring, but for the majority of sites no repeat observations were carried out.

6.6.4 SoilWatch

Soil monitoring in NSW was continued in a less structured, voluntary way through the *SoilWatch* program.

This soil health program is a collaboration between the NSW Department of Planning, Industry and Environment (DPIE), NSW's Local Land Services (LLS) and individual landholders. Under this program, paired sites (undisturbed and treatment) are established on individual farms to measure impacts of land management practices through changes in soil health. Since the program began in 2008, about 300 monitoring sites have been established.

At each site, soil samples are collected and dispatched for laboratory testing. The measures used are:

- EC
- Total organic C
- Bulk density
- Moisture content
- Field texture
- Gravel content (%)
- CEC and exchangeable Al, K, Mg, Na
- Total P

6.7 Smaller-scale Australian studies

There have been various studies of soil factors and their relationship to forestry in Australia published in recent decades, both in plantation and native forests. These have, however, almost always addressed specific forest productivity issues rather than assessments of soil condition, productivity or health that are widely applicable across regions or states.

A recent and influential study, particularly in the context of the widespread damage caused by the 2019–2020 bushfires in eastern Australia, is Bowd *et al*. (2019)'s research into the abiotic effects on soil of human disturbance in forested environments. This study measured soil chemical characteristics across a multi-century chronosequence of clear-cut and post-fire salvage logging areas in (again) the *Eucalyptus regnans* (mountain ash) forests in the Central Highlands of Victoria. In demonstrating that forest soils are significantly affected up to at least 80 years after major disturbance, and in some cases as long as 150 years, the study used the following measures at soil depths of 0–10 cm and 20–30 cm:

- Ammonium (NH_4^+)
- Available P
- Available K
- Nitrate (NO_3^-)
- Total organic C
- Total S.

The study did not measure nutrient uptake by vegetation but concluded, based on site comparisons, that disturbance intensity and frequency is a major determinant of forest soil composition regardless of stand age or nutrient uptake.

Turvey and Smethurst (1994) investigated the use of soil profile types as classes for managing nutrient status and productivity of stands of *Pinus radiata* in Gippsland, Victoria. They found that N and Ca in foliage, N, P, and K in forest floor litter, and all measured chemical variables in soil were correlated strongly with wood production, though analyses of variance of individual chemical variables across soils did not show exclusive and consistent grouping of similar soil profile types. In this area, soil types based on observable soil profile criteria were reflective of soil nutrient status and were therefore suitable for use as classes for managing soil fertility and wood volume production.

Costantini *et al*. (1997) examined the maintenance of soil fertility and protection of watercourses from erosion in second rotation *Pinus* plantations in southeastern Queensland, finding that challenges remained, and development of management systems to ensure consistent operational quality should be continued.

Neave and Raison (1999) investigated soil N availability under forests of different composition and structure in southeastern NSW, and the effects of harvesting and burning. Their soil investigations consisted of 4 sites in Kioloa State Forest, each a 0.25 ha (50 × 50 m) site divided into 4 25 × 25 m sub-plots. Intact soil cores were collected, along with disturbed soil samples heated to various temperatures to simulate slash-burning after harvest, and tested for N mineralisation. The results indicated that soil disturbance alone did not stimulate N mineralisation in any of the soils, a result which explained poor *Eucalyptus maculata* regrowth. Heating produced considerably more mineralisation of N, although there was also a cost in terms of volatile loss of organic matter and nutrients, convective transfer of ash (including N and P) and other factors, and potential stimulation of fire weed species.

Benyon et al (1999) undertook species evaluation trials of *Eucalyptus camaldulensis* and *E. occidentalis* on a saline discharge site near Wellington, NSW. The study found that increased soil salinity impacted growth height, stem diameter, crown volume and mean leaf area. Later trials in

Wellington evaluated the survival and growth of 24 native tree species under saline conditions and found for most accessions, trees survived and grew better in non-saline soils (mean EC <2 dS/m) (Marcar *et al.* 2003). These findings point to the relationship between soil salinity and native tree health.

Bubbla *et al.* (2000) explored the impact of site preparation techniques on soil and N loss and runoff during establishment of *Araucaria cunninghamii* (hoop pine) plantations in southeast Queensland, concluding that only relatively small areas of the catchments were contributing to runoff and that most erosion occurred within the first 2 years following establishment, after which erosion was no more than natural background levels. Annual losses of N were equivalent to estimated annual inputs from the atmosphere and biological fixation.

Chikumbo *et al*. (2001) discussed the term 'forest sustainability' and its change over time, from wood supply to preservation of ecological vitality of forest ecosystems. They concluded that more work needed to be done on developing techniques for monitoring implementation and effectiveness of procedures for achieving forest sustainability, and proposed a conceptual framework for integrating strategic planning with operations and monitoring.

Constantini and Doley (2001a, b, c) examined compaction by forest harvesting machinery in the *Pinus* plantations of Queensland, and soil parameters that might be used to predict compaction risk. They found that soil moisture was the most sensitive parameter in predicting rut depth, though not at rut depths beyond 5 cm, indicating that predictive models could merely supplement, rather than replace, the 'reactive' approach taken in Queensland to limit forestry operations to those not rutting the soil to depths of 10 cm or more.

Cromer *et al.* (2002) investigated the growth of plantation eucalypts after application of N and P fertilisers on low-nutrient soils in Tasmania, and found that stem volume increased directly with rate of application but that establishment of plantations on such soils was probably not economically viable. Fertiliser application on more inherently fertile soils had a delayed and sigmoidal response and showed significant increases in productivity, to the extent that fertiliser application in such circumstances was probably cost-effective.

Mahmoudzadeh *et al*. (2002) investigated sediment yield from cultivated, pasture and native forest catchments on granite soils in the Bathurst region of NSW, and concluded that cultivated catchments produced the most sediment, at rates that were high by Australian standards and were not effectively predicted by either the Modified USLE, Soiloss or Revised USLE models. They recommended that more research was required to test and develop soil loss predictions under Australian conditions.

Eldridge and Wilson (2002) compared the C content of soils and vegetation between roadside reserves and adjacent paddocks in the temperate box woodlands of eastern Australia, finding that differences were mainly due to C storage in vegetation, concluding that the retention of native vegetation was likely to be more effective for retaining C in the landscape than enhancing C storage under cropping or grazing enterprises.

Stone *et al*. (2003) carried out an initial investigation of methods that could be used to monitor forest health, and thereby allow Australia to effectively report against Criterion 3 of the Montréal Process (forest health and vitality). They concluded that tree crown condition, as both a key attribute of forest health and one readily measurable by standardised assessment (both remotely and in-field), was a suitable indicator, and went on to propose a Crown Damage Index by which this indicator could be summarised and communicated.

Turner and Lambert (2005) explored the linkages between soil and nutrient processes and the extensive crown dieback of eucalypt forests on the east coast of Australia. They found evidence of long-term accumulation of N in long-undisturbed stands, and consequent nutrient and biochemical imbalances in foliage, leading to the leaves being more attractive to insects and other folivores. They concluded that frequent low-intensity fires maintain stable N levels and thus maintain healthy stand structure and growth.

Packer *et al*. (2006) investigated the use of logging residues to protect forest soils during mechanical harvesting, and found that regeneration along snig tracks treated with large-diameter logging debris that is later lifted and burned—a practice known as 'cording' that is promoted by the Tasmanian Forest Practices Code—was consistently inferior in quality and quantity compared to untrafficked areas, and that the practice of cording was ineffective unless the debris was left *in situ*. They concluded that more research was required.

Wang *et al*. (2008) explored the influence of deep weathering profiles on occurrence and geochemical character of groundwater in the pine plantations of coastal southern Queensland. They identified lower soil salinity following the establishment of the plantations.

Wilson *et al.* (2008, 2010) tested a range of potential soil condition indicators and their suitability to detect differences in soil condition between these land-use types. A range of soil properties showed no significant difference between land-uses and could be rejected as indicators. However, significant differences existed between the land-uses and soil depths for a range of the other soil parameters determined (bulk density, C, N, P, EC, and Na). The studies provide a basis for sampling monitoring design.

An investigation into the benefits of reforestation for Ferrosol soils in the Lake Baroon catchment of south-east Queensland (Gageler *et al*. 2014) explored the response of soil properties and functions to restoration of riparian rainforest restoration. It was found that the main benefit was (perhaps not unexpectedly, given the type of soil) recovery of soil structure, causing decreases in bulk density and increased infiltration and thereby potentially reducing runoff, soil erosion and turbidity in downstream waterways. Soils were sampled at 0–15 cm and 15–30 cm depths and measures included:

- Bulk density
- Infiltration (disc permeameter)
- Total N
- Total organic C
- Nitrate (NO_3^-)
- Ammonium (NH_4^+)
- Particle size analysis.

Beh *et al.* (2016) used ground-based measurements of stem shape and taper in the butt swell section of individual *Pinus radiata* plantation trees to predict soil depth. This works has implications for soil mapping and forest management, including C accounting.

In exploring the vulnerability of Australian production forestry to climate change, Keenan (2017) identified a need to translate risk and vulnerability assessments into impacts on timber supply, C sequestration, forest composition, soil processes and hydrology, as well as changing fire frequency and intensity, and further identified deficiencies in knowledge required to drive adaptation responses.

Riggert *et al*. (2017) assessed the impact of timber harvesting on physical soil properties (on loess soils in Germany) and found that soil stress impacts from modern forest machinery were very high, resulting in compaction of soil materials, some of which was considered irreversible. They recommended adoption of machinery with lower wheel load (e.g. minimising machine weight and/or using wide rubber tracks) and harvesting at lower levels of soil moisture.

Farrell and Prober (2020) observed that transformation and movement of organic matter in litter and soil, for example during a major fire event, can increase soil's surface water repellence, reducing the water available to plants for their reestablishment and recovery. This reinforces the importance of organic matter as a measure of soil health.

Bennett *et al.* (2020) examined variations in soil organic carbon (SOC) stocks in temperate forests in south-eastern Australia. The study compared current Australia-wide databases and identified previous underestimation of forest SOC concentrations, and confirmed the fine finding of Grey *et al.* (2016) that climate variables (precipitation and temperature) were of greater importance to the prediction of SOC concentrations than terrain and fire-history variables. The study acknowledged the lack of reliable estimates of SOC distributions within many forested regions, due to a mismatch of sampling intensity and spatiotemporal variation, highlighting the importance of sampling coverage and methods harmonisation

6.8 TERN

The Terrestrial Ecosystem Research Network (TERN) was established as a component of the Australian government's National Collaborative Research Infrastructure Strategy (NCRIS). Established in 2005, NCRIS is a program for the collaborative development of national research infrastructure.

TERN's role is to support research leadership in terrestrial environmental monitoring and modelling for long-term national benefit through providing infrastructure for the use of researchers. As part of this role, it sets up and encourages use of nationally-consistent standards for measurement of ecosystem condition under a subprogram called TERN Surveillance. Under their core program, AusPlots, they have established standards for monitoring in rangelands (AusPlots—Rangelands; White *et al*. 2012) and tall forests (AusPlots—Forests; Wood *et al*. 2015).

TERN provides digital data entry tools on PDA or smartphones to support data collection using these standards.

6.8.1 AusPlots—Forests

The 'research question' targeted by AusPlots—Forests is to "improve our understanding of tree growth, forest productivity and carbon dynamics in eucalypt forests in relation to macro-environmental gradients across Australia" (Wood *et al*. 2015).

AusPlots—Forests standardises on a 100 × 100 m (1 ha) plot design, which is divided into 25 subplots of 20 × 20 m and is located in a determined representative site with minimal disturbance using GPS coordinates. Basic landform features are described along with detailed collection of floristics information and plant specimens, and samples for soil analysis and metagenomics.

Soil samples consist of moderately to highly decomposed litter found at the base of the litter layer, and soil cores to 10 cm depth. There is no other collection of soil information.

6.8.2 AusPlots—Rangelands

AusPlots—Rangelands takes a somewhat different approach. Its purpose is to "establish permanent plots throughout the Australian rangeland bioregions where baseline surveys of vegetation and soils will be conducted" (White *et al.* 2012) for long-term monitoring of environments that cover ~81% of the Australian land mass.

Whilst the plot design is the same as the later AusPlots—Forests standard, the procedure takes advantage of the improved sky coverage in rangelands by located sites precisely using differential GPS, and also mandates (for their fully-described plots) collection of 360° panoramic photography, collection of flora samples for genetic analysis, and considerably more landscape and soil information including levels of disturbance, site drainage, surface condition and a soil description to at least 1 m depth using either a pit (preferred), core or auger.

Soil samples of 500 g mass are to be collected at 10 cm increments down the soil profile, with care taken not to sample across horizon boundaries. It is intended that a pedologist describes the profile, preferably onsite and *in situ*. Bulk density core samples are also collected at 0–10 cm, 10–20 cm and 20–30 cm depths, whilst surface samples to 3 cm depth are also collected for soil metagenomic analysis.

It is noted that "*it is anticipated that the methods in this manual will be highly applicable to other Australian environments*" (White *et al.* 2012).

6.8.3 Measures of soil health

The AusPlots standards do not indicate what soil analyses are to be performed, however information on TERN's Landscape Data Visualiser (https://maps.tern.org.au) suggests that the measures include:

- Bulk density
- (Total) organic C
- Particle size analysis
- pH ($CaCl_2$)
- Available water-holding capacity
- Total N
- Total P
- Effective CEC
- Depth of regolith*
- Depth of soil*.

* As the generation of this data is not possible using the data recorded during an AusPlots—Forests investigation, it is assumed that this data comes from another source—e.g. the Soil and Landscape Grid of Australia (SLGA).

7 Soil quality assessment—variations on the theme

7.1 Measures and methods

The explosion in soil data collection across multiple land uses around the world is reflected in the plethora of soil quality assessment and monitoring tools introduced over the last 30 years, each using a mix of measures to assess soil health (Bünemann *et al*. 2018). They summarise the use of various indicators into a table (see Figure 6 below), which groups indicators into biological (green), chemical (red) and physical (blue) categories and shows the frequency of their use in 65 soil quality assessment approaches.

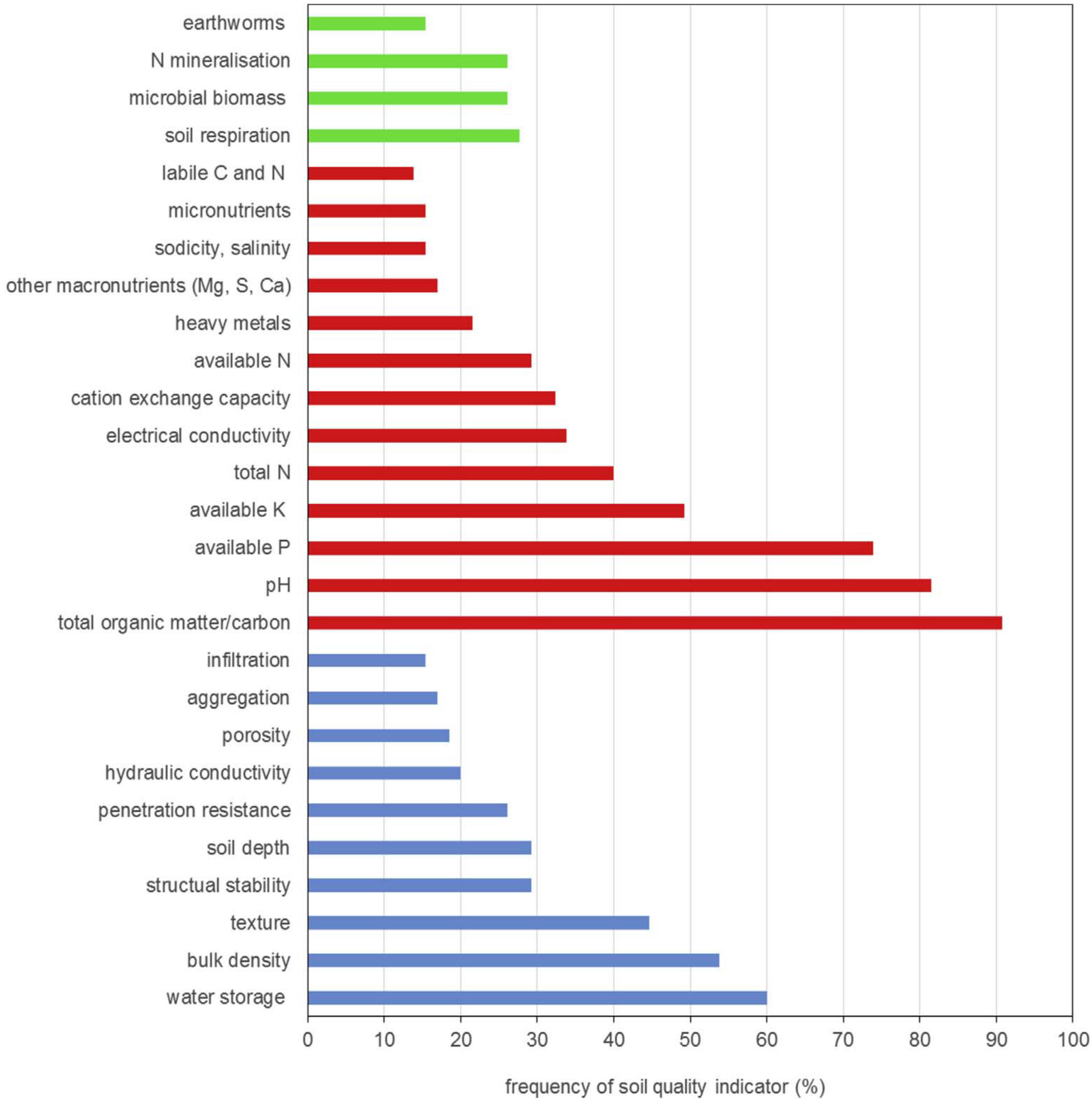


Figure 6 Frequency of use of indicators in soil quality studies (from Bünemann et al*. 2018)*

As can be seen, total organic matter/C and pH are the most frequently used indicators, followed by available P, various measures of water storage, and bulk density. Soil texture, available K and total N are also frequently used. The average number of indicators used in each approach was 11, though it was observed that this number is decreasing over time due to the impact of practical and financial limitations.

Most studies included at least one indicator from each category, however biological and biochemical indicators are generally under-represented despite their importance to soil function, their sensitivity to environmental conditions and their influence on ecosystem health, and are generally limited to 'black-box' measurements like microbial biomass or soil respiration.

7.2 Qualitative assessment

The USDA's Natural Resources Conservation Service established its Soil Quality Institute in 1993, its mission statement being to develop and disseminate tools for soil quality assessment (Ditzler and Tugel 2002). The Institute recognised that directly measuring the quality of a soil was difficult, if not impossible, and that a better approach was to identify the soil functions of interest and then develop a set of indicators that would infer the ability of the soil to perform those functions.

A quantitative approach involving detailed field and/or laboratory measurement of soil physical, chemical and biological properties was recognised as well-suited for trained professional users, but less so for land managers. The Institute therefore developed a qualitative approach for land managers, relying on measures that can be simply observed and qualified—having observed that, whilst subject to internal bias, such measures have been found to compare well to quantitative measures (Liebig and Doran 1999). The Institute produced a design guide that could be used to develop what they referred to as 'soil quality cards'—simple forms allowing land managers to qualitatively describe indicators of most relevance to their local conditions. The content of each card is developed through facilitated meetings of landholders and agricultural professionals.

By 2002, 7 Soil Quality Cards had been developed for different agricultural regions of the USA encompassing 32 physical, 12 biological, 9 chemical and 15 plant or residue indicators of soil quality. Many indicators are common from card to card but may be described in a different way, reflecting local landholder terms and concepts. Each indicator is rated from 1 (poor) to 9 (good). Example indicators include:

- Compaction
- Drainage
- Infiltration
- Nutrient-holding capacity
- Salinity
- Soil organisms
- Earthworms
- Residue decomposition
- Crop vigour.

Because the ratings are subjective, observations made by different people cannot be directly compared, and the indicators and ratings selected represent the view of farmers, not other user groups that may have different perspectives on soil health. To provide a quantitative aspect to the process, a test kit was developed to provide farmers with a simple, easy-to-use, inexpensive and efficient means of measuring soil quality. The kit allows farmers to measure the following indicators:

- Soil respiration
- Earthworm count
- Infiltration rate
- Bulk density
- Water content
- Slaking
- Aggregate stability
- pH
- EC
- N (NO_3^-).

Preceded by planning site location and timing, the actual field sampling takes 1–2 hours, with a further 2–3 hours later for drying and sieving samples and measurement. A 30 cm deep excavation is used for each assessment.

The Institute considered (Ditzler and Tugel 2002) that the approach was successful in describing the importance and the interactions of the physical, chemical and biological components of soils, and in allowing farmers to evaluate the impact of different forms of land and soil management.

7.3 Soil quality indices

The work of Amacher *et al*. (2007) is one of a number of efforts around the world to develop soil quality indicies (SQIs), which summarise the often complex measures of soil health into a single number useful for indicative and comparative purposes.

Noting that individual physical or chemical properties may be of little value in assessing overall soil health, Amacher *et al*. (2007) integrated 19 measured physical and chemical properties of forest soils into a single number that is intended to serve as the soil's 'vital sign' of overall health. The measures that contribute to the index are:

- Bulk density
- Coarse fragments (% volume)
- pH
- Total organic C
- Total N
- Elements (Al, Ca, Cd, Cu, Fe, K, Mg, Mn, Pb, S, Zn)
- Phosphorus

Each of these measures is given an index value depending on the range in which the value falls—e.g. total organic C's index value is 0 when <1%, 1 when between 1–5%, and 2 when >5%. These index values are summed to give the final SQI value.

The paper recognises that several of the individual soil properties are related—e.g. bulk density is influenced by soil organic matter, which is indirectly measured by total organic C and total N.

Early work included Andrews *et al.*'s (2004) *Soil Management Assessment Framework*, which progressed prior investigations by determining a set of indicators that could be applied across a variety of climates, soil types, management practices and end-user goals. The studies in different parts of the USA used a subset of those indicators—the choice of indicators was constrained to those already available, as the study only used existing data—which were chosen using an expert system of decision rules. The total set was:

- Nematode maturity index
- Metabolic quotient CO2
- Bulk density
- Available P
- Total organic C
- Microbial biomass
- Potentially mineralizable N
- pH
- Macroaggregate stability
- Soil depth
- Available water capacity
- Electrical conductivity
- Sodium absorption ratio.

Indicators were then transformed into unitless scores based on site-specific algorithmic relationships to soil function (in a similar way to Amacher *et al.* 2007), and (optionally) a final SQI was generated from these scores. The SMAF has since been systematised into an online assessment tool (http://soilquality.org/tools/smaf_intro.html) for the calculation of the SQI.

Erkossa *et al*. (2007) tested the SMAF in the Ethiopian Central Highlands, finding that it was a viable tool for assessing performance of land management methods against soil quality but required modification to fit the prevailing land management systems and soil characteristics. The indicators used were:

- Microbial biomass C
- Bulk density
- Aggregate stability
- Soil organic C
- pH
- Available water-holding capacity
- Available P.

Mukherjee and Lal (2014) compared 3 SQI methods, including a simple additive SQI similar to Amacher *et al.*, using data from 72 on-farm sites in Ohio, USA, in order to generate a "user-friendly and credible" index for improving soil quality, increasing crop yields and reducing ecological footprint of farm operations. Indicators were added for:

- Particle size
- Aggregate stability
- Soil strength
- Water content.

At least some of these measures relied on author's opinion rather than qualitative results.

A weighted-additive method was used to generate the second SQI, with soil textural and strength measures incorporated into a single measure for root development and chemical factors contributing to a single value for nutrient storage capacity.

A statistically-based model delivered the third using principal component analysis, which generates a minimum dataset by removing interrelated variables whilst retaining most of the variation present in the original data.

All 3 methods proved to be closely correlated, but the third had the most predictive value in terms of crop yields. It was also noted that soil fertility and microbial parameters would be required to deliver a fully effective prediction.

There are a number of other SQIs in development or operation, however Bünemann *et al*. (2018) observed that indexes may not necessarily be very meaningful, as soil quality is best assessed in relation to specific soil functions, and that graphical representation of soil health may be more effective in visualising and communicating soil health to end-users and the community in general.

7.4 Digital soil mapping

DSM involves the spatial extrapolation or prediction of soil properties and classes across geographic areas (McBratney *et al*. 2003). This science has developed in the last few decades as computer processing power and storage has advanced, Geographic Information System (GIS) software has developed, and availability of data has increased, particularly in terms of so-called 'covariates'—datasets that can be used to predict soil attributes, such as climate, remote sensing, digital elevation models and radiometric imaging.

DSM aims to generate surfaces of continuously estimated soil attributes, along with measures of their uncertainty, so that areas where actual measurements are non-existent or sparse can be described. In turn, these surfaces can be used as inputs into more complex models that simulate entire environmental processes and predict change—e.g. under climate change scenarios.

Most DSM approaches use statistical models that establish environmental correlations between point data and spatial coverages of covariates, whilst the more advanced incorporate data mining and machine learning to avoid pre-existing assumptions about the relationships between soil attributes and their covariates.

Examples of significant DSM projects or products include the Soil and Landscape Grid of Australia, SLGA (Grundy *et al*. 2015), a nationally consistent continental-scale set of continuous soil attributes combining existing soil data, soil spectroscopy, soil modelling and soil inference systems. These surfaces are modelled at 3 arc second (~90 m) resolution at 6 soil depth intervals down to 2 m and are accompanied by reliability maps and statistics to provide the user with confidence in their use. Attributes include:

- Sand (%)
- Silt (%)
- Clay (%)
- Bulk density
- Available water capacity
- Soil organic C (%)
- pH ($CaCl_2$)
- Effective CEC
- Total P
- Total N
- Soil depth.

Another is the digital soil mapping developed for NSW (OEH 2017), which parallels and complements both the SLGA and conventional soil map datasets for NSW by providing surfaces of key soil attributes over 6 soil depth intervals to 2 m at 100 m resolution. Attributes include:

- Soil organic C

- pH
- CEC
- Sum of bases
- Total P
- EC
- ESP
- Clay (%)
- Sand (%)
- Silt (%).

7.5 Pedotransfer functions

The term 'pedotransfer function' was defined by Bouma (1989) as a means of "translating data we have into what we need". Pedotransfer functions (PTFs) are predictive functions that add value to basic soil information by translating them into estimates of more complex, laborious and/or expensively determined soil properties that are key measures of soil function and health. The development and current state of PTFs has been recently summarised by Van Looy *et al.* (2017).

PTFs have been used for many years, though not known as such—traditionally predictions have been made by 'rule-of-thumb' using expert knowledge. More recently, however, these functions have been derived mathematically from existing data and developed into computer models to provide inferences with maximum accuracy and minimal uncertainty, which allows soil ecosystem services to be quantified. Statistical techniques used include linear and non-linear regressions, support vector algorithms, regression trees and artificial neural networks.

In their most sophisticated form, these functions have been incorporated into so-called 'soil inference systems' which automatically match subsets of soil properties to applicable PTFs—for example, the Soil and Landscape Grid of Australia (Grundy *et al.* 2015) is implementing a soil inference system to improve the mapping and provide additional predicted functional soil properties, including those informing process-based soil and production models. PTF outputs may be further integrated into models that simulate entire environmental processes, such as so-called 'land surface models'. Given the pressing need to better understand climate change processes, C cycling is a particular focus of these complex, large-scale developments.

There is also a developing field of biotic process parameterization, for some time an under-studied area, including modelling soil microbial diversity and C-N processes, in which soil water availability appears to be a primary driver. Also significant is the role of novel indicators such as soil spectroscopy (see Section 7.6.1), which allow the rapid acquisition of soil information for use by PTFs.

There are 2 broad types of PTFs: continuous (which use continuous quantities, such as clay content or organic matter content) and class (which use classes of soil properties, such as soil type). Both have their uses—continuous are usually employed to parameterise soil processes in simulation models of water, energy and C cycles, particularly in terms of soil hydraulic properties. Class PTFs (also referred to as 'look-up tables') are generally simpler techniques that provide estimated parameters by commonly recorded classifications such as soil type or texture class.

It is important to note the role of scale in applying PTFs, as those derived in the lab at the soil pore scale are not applicable at field scale and estimates at landscape level do not equate with regional-scale estimates. Further, it is unwise to apply a PTF outside the geographic region or soil type that supplied the data with which it was developed, as accuracy is likely to suffer. Nonetheless, PTFs are very powerful tools that are widely applicable across many disciplines of earth science and are being developed in numerous productive directions (Van Looy *et al.* 2017).

7.6 Novel indicators

7.6.1 MIR and NIR spectroscopy

Infrared spectroscopy involves the interactions of matter with infrared radiation, relying on the fact that molecules absorb frequencies of radiation that match the harmonic oscillations of their atomic structures. In principle, measurement of these characteristic vibrations allows the composition of a material to be determined to a high level of precision.

Infrared spectroscopy is used in a variety of areas, such as industrial chemical processes, forensic analysis, pollution control and semi-conductor microelectronics, and has the potential to revolutionise soil data collection, as measurements can be carried out much faster and with less expense, and several soil properties can be inferred from a single measurement of a small (~10 g) powdered sample.

Novel indicator technologies (left to right): a laboratory MIR spectrometer, a portable field MIR spectrometer and a portable XRF analyser.

Scientists around the world have demonstrated the practical application of MIR and NIR technology in the laboratory for rapid and accurate prediction of soil properties, including validated predictions from MIR spectra for Total C (LECO), organic C, $CaCO_3$ equivalent, total clay, cation exchange capacity (CEC), 1,500 kPa water and pH in both water and $CaCl_2$ in certain soil types. MIR is now considered an ideal technique for quantitative analysis in soils. The technique reduces sample preparation to a minimum and has undergone substantial development over the last couple of decades such that reliable calibrations for diverse soils can be achieved with no sample dilution. (Seybold *et al.* 2019)

It should be noted that MIR does not as yet provide the ability to test for all attributes that may be of interest in assessing soil health, and requires a proportion of samples to be conventionally tested for calibration purposes so that the analysis of the MIR spectra delivers accurate predictions. Also, whilst portable MIR and NIR spectrometers have been developed, they are yet to reach a stage of maturity suitable for field soil assessment. Nonetheless, MIR spectroscopy has the capacity to significantly increase speed and reduce cost of laboratory soil analysis, and its use will be a significant enabler of soil monitoring going forward.

A significant use of soil spectrometry in Australia was during the development of the SLGA (Grundy *et al.* 2015). Site data was complemented by spectroscopic estimates using the National Soil Visible-

Near Infrared Database (NSVNIRD), which improved data coverage over large areas of central and north-western Australia where laboratory soil test data is sparse.

7.6.2 X-ray fluorescence (XRF)

X-ray fluorescence involves the emission of characteristic 'secondary' fluorescent x-rays from a material bombarded with high-energy x-rays or gamma-rays. Already widely used in elemental and chemical analysis in geochemistry, forensic science, archaeology and art history, XRF has shown great utility in evaluation of elemental concentrations in soil (Zhu *et al*. 2011), results which can be interpreted to infer a variety of soil characteristics. Initial use was investigating contaminated soils, but since then XRF has been used to measure variables such as soil texture, pH, K, Ca, Fe, Mn and Sr (Yang *et al*. 2020). Water and organic matter content of samples can affect results, so correct sample preparation is an important consideration. XRF spectrometry can also be used for plant analysis.

7.6.3 X-ray diffraction (XRD)

A related technique to X-ray fluorescence, X-ray diffraction involves the interaction of directed monochromatic X-rays with finely-powdered samples, which produces constructive interference and diffracted X-rays. By scanning the sample through a range of angles, diffractions are generated that identify the crystalline structures and arrangement of atoms of the sample. XRD is a popular technique for determining the mineralogy of crystalline materials and can be used to identify the mineral components of soil (Singh and Agrawal 2012) and weathered rock, in particular the identification of clay minerals.

7.6.4 Soil metagenomics

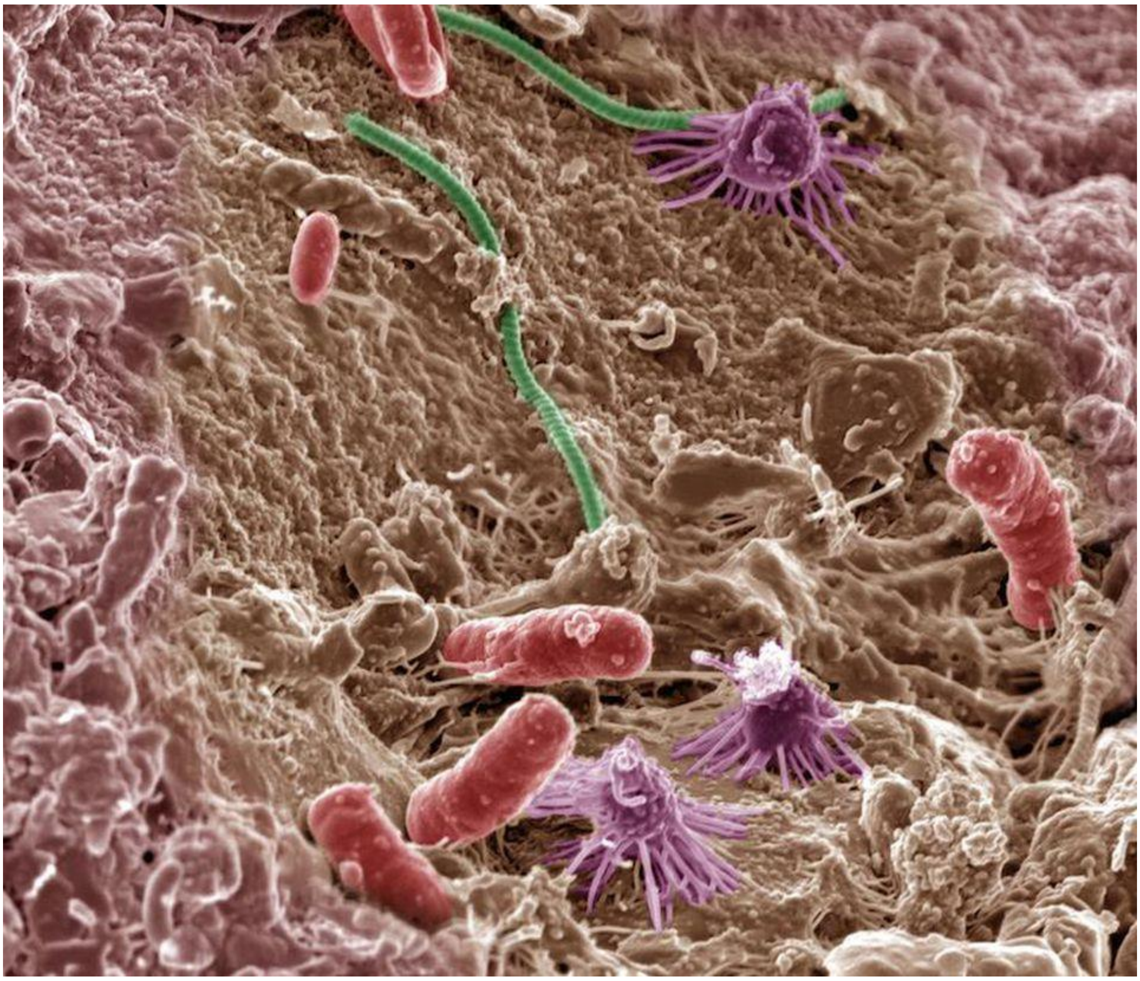
Soil organisms play a central role in soil functioning (Bünemann *et al*. 2018). However, because of difficulties in measurement, these communities, which are critical to soil function and health through their role in nutrient uptake and cycling and the processing of organic matter, have been relatively little studied. Much of the C in a soil is contained within its microbial community, and undoubtedly soil microbes play a key role in creating and maintaining soil fertility and soil health. Soil biota are also considered to be the most sensitive indicators of soil quality due to their responsiveness to changes in environmental conditions (Bünemann *et al*. 2018).

A significant problem in measuring the microbiological component of soil is that most of the microbes involved cannot be cultured in the laboratory, making assessment of genetic diversity very difficult. Metagenomics provides a way of bypassing these difficulties. It involves sequencing DNA from a sample without firstly culturing and isolating the individual organisms. By isolating DNA from a sample and cloning large segments of DNA, it allows libraries of genomic material to be developed. These 'genetic fingerprint' assessments of microbial communities can be used to assess the biological health of soils in a standardised and directly comparable way, as well as measure the effects of different land uses or land management practices. Due to seasonal changes, rainfall variations and other factors, comparisons of soil biota health using metagenomics require use of paired sites—i.e. measurement of natural or semi-natural conditions at a control site next to each managed site, so that the effect of management may be measured independently of other environmental variables.

As mentioned in Section 6.7 (above), the TERN monitoring standards include a requirement to collect soil samples for metagenomic analysis. TERN's field sample library includes a collection of several thousand metagenomic soil samples that are available for use by the research community. Also, the Atlas of Living Australia includes a soil microbial diversity database, the Biomes of

Australian Soil Environments (BASE) system, for the recording of soil metagenomic information on a collaborative national basis (Bissett *et al*. 2016).

Uses of metagenomic information in Australia are so far fairly limited but diverse. Published work includes exploring reasons for low N use efficiency of sugarcane. Previous work (Robinson *et al*. 2011) had concluded that N applied to sugarcane soils is diminished within 2–3 months, although the plant requires N from soil for at least 6 months. Metagenomic analysis confirmed that manipulating fertilized rates did not improve yield by enriching nitrogen-fixing bacteria and indicated that balancing crop yields and nutrient pollution required more understanding of how soil microbial communities react to fertiliser use (Yeoh *et al*. 2016). Other uses include using soil microbial communities to assess rehabilitation after iron ore mining (Gastaeur *et al*. 2019).



An electron micrograph of soil micro-organisms. Photo: Alice Dohnalkova/PNN.

8 Discussion

Changes in key soil properties are inextricably linked to forest health and should be monitored to inform appropriate forest management actions and strategies.

The forest soil monitoring systems implemented in the United States, Europe and New Zealand are impressive in their scale, rigour and data-driven foundation, and provide good examples for an equivalent system designed for the specific conditions of NSW forests and forest soils.

In comparison, existing sustainable forest monitoring in Australia is on the whole fragmentary, inconsistent and based on a set of criteria and indicators that are not effective in either establishing a baseline condition or tracking changes due to land management or disturbance. As discussed earlier, the existing indicator framework—both MIG's revised national indicators and the NSW EPA's derived ESFM indicators—do not provide a viable foundation for the development of a forest soil monitoring program in NSW.

This shows that the purpose and design of a monitoring system, the choice of variables to be measured, and the indicators that are to be assessed, need to be determined with considerable care. Bünemann *et al*. (2018) provides assessment of many (albeit mainly agricultural) soil condition/health/quality assessments, observing that:

- the choice of relevant attributes, measures and interpretations is not straightforward, particularly given the inherent complexity and site-specificity of soils, effects of previous land use and trade-offs between ecosystem services
- some indicators are difficult to use (e.g. bulk density) or expensive to measure, resulting in otherwise useful measures being discarded
- pedotransfer functions can be useful in filling gaps but are not necessarily accurate enough to be reliable
- evaluation of soil quality is generally not targeted to specific soil threats, functions and ecosystems services
- soil quality information has rarely been specific enough to allow effective use by land managers or in policy development.

Nonetheless, the paper does not deprecate the value of scientifically-based soil quality or soil health in environmental assessment, though it suggests that end-users should be heavily involved so that results can be effectively interpreted, and behavioural change made so that soil and environmental health is improved.

In this context, whilst this review makes some recommendations on indicators and methods, it is suggested that the set of final measures and techniques of measurement of soil health should be determined collaboratively with stakeholders and end users, including those responsible for forest management under the various tenures involved, to ensure that the indicators are achievable, measurable and relevant to practical action for the assessment and improvement of NSW forest soil condition.

Furthermore, the indicator and monitoring systems should be adaptive, capable of rapidly adjusting to changing circumstances and capable of pivoting easily to address specific issues of concern. After all, as Doran and Zeiss (2000) indicate, the true goal is sustainable natural resource management—indicators of soil quality, and other measures, are a means toward that end.

In this context, the following principles are proposed for the NRC soil health in forests monitoring program:

1. **Soil health should be integrated into health assessments of forest ecosystems.** Soil monitoring should be co-located with ecological investigations into integrated sites, which should be representative of forest types under different environmental conditions and site histories and should be subject to repeat observation on regular timescales (at least 1 visit per 10 year cycle).
2. **Soil health and stability monitoring in NSW forests should materially contribute towards accurate and meaningful Australian reporting against the criteria and**

indicators set out by the Montréal Process. This is an important national and state commitment.

3. However, **monitoring must also provide a meaningful framework for evaluating forest soil management**, rather than just support arbitrary reporting purposes**.**
4. **There is no substitute for real data.** Modelling can assist in establishing a baseline of ideal soil health and stability—however, given the complex, multi-decadal interactions between ecosystem and soil condition and health, and the limitations of our existing knowledge, collection of comprehensive field data is critical to meeting the needs of this project. The establishment of a network of permanent monitoring sites in forests subject to regular repeat observation must be a high priority—modelling can help extrapolate results from monitoring sites but can never replace them. Modelling and monitoring should be seen as complementary (McKenzie *et al*. 2002).
5. **Site history is also an important variable.** Field monitoring must be carried out in the context of previous disturbance of the site, whether by human-induced change (e.g. clearing, clear-fell or selective logging, revegetation) or natural/semi-natural change (e.g. bushfire). Since studies have suggested that evidence of past disturbance can be detected in soils as long as 150 years later (Bowd *et al*. 2019), site history will need to be considered on multi-decadal timescales.
6. **Monitoring needs to be a long-term commitment.** To be effective, forest and soil monitoring will require provision of suitable expertise and ongoing, long-term resourcing, so as to avoid the failures of previous monitoring efforts.
7. **Robust, repeatable protocols should be used for baseline establishment and ongoing monitoring.** The TERN standards provide a useful avenue towards monitoring soil health on a consistent cross-jurisdictional level.
8. **Data collected should be stored and made available through state and national information systems** to maximise its value and accessibility.

9 Recommendations

9.1 Baseline

Establishment of a baseline condition for soils in NSW forests will be provided by digital soil modelling and mapping that is informed by as much actual soil data as possible. Therefore, the modelling phase should be preceded by a 'data trawl' in which all available data from all forest tenures, types and managers in NSW is gathered, utilised and exposed for analysis.

9.2 Monitoring design

Hierarchies of monitoring are a part of successful forest and soil monitoring programs around the world, and such an approach is recommended for NSW forest and soil monitoring.

'Reference sites', at which comprehensive soil descriptions and samples are taken, should be located across forest types and tenures, selected through stratified random sampling techniques on the basis of soil landscape mapping units.

It is preferable that these sites be permanent and be co-located with ecological investigations into integrated site descriptions, which should be representative of forest types under different environmental conditions and with known site histories, as undisturbed as possible, and subject to repeat observation on regular timescales—e.g. 1 visit per ~10 year cycle—using a comprehensive set of indicators (see Section 9.3. As an indication of the level of data required, these sites could be based on the AusPlots—Rangelands specification (White *et al.* 2012). Measurements from these sites are required to provide a solid evidence basis for forest and soil condition, stability and change, and to allow results from other sites to be calibrated and contextualised.

One approach is to develop a network of sites based on high and low-resolution data collection, whereby the limited number of reference sites should be supplemented by a much larger number of less detailed sites selected through stratified random sampling techniques, again based on soil landscape mapping units. These sites would include immediate and ongoing sampling in areas that subject to significant disturbance or alteration in land management—e.g. fire, timber harvesting, severe weather events—that are likely to have affected forest or soil health. As an indication of the level of data required, these sites could be based on the AusPlots—Forests specification (Wood *et al*. 2015), though with an initial soil description. The areas characterised by these sites would be revisited on a ~5-year return period, a period that could be adjusted based on the anticipated rate of change of the variables being measured. Given the experience of studies in other areas (e.g. Lawrence *et al.* 2016) it is not necessary that individual sites be revisited, but that regular sampling be undertaken of sites within identified monitoring units on a regular basis. The sites identified for sampling during the initial analysis therefore represent a super-set from which a subset of sites is selected for sampling at each rotation.

Detailed monitoring sites should be part of a broader monitoring design that includes rapid sampling of large areas of forest soils, leveraging novel indicators such as MIR to allow throughput of numerous samples at low(er) cost. These 'grab' samples should be taken from the top 0–10 cm of mineral soil and tested for a reduced set of key indicators (see Section 9.3). They should be accompanied by field-based qualitative assessment of vegetation and soil disturbance. Any ecological investigation would ideally include at least this level of soil data collection. There need to be a sufficient number and density of these samples to provide a firm analytical foundation for soil condition monitoring in NSW forests—in particular, to provide a sufficiently large and spatial extensive dataset to avoid limitations of applicability and accuracy experienced by previous monitoring programs.

Soil samples should be archived for reference, calibration and future testing for other indicators (e.g., in the existing NSW soil archive at DPIE's Yanco laboratory) whilst soil data should be stored and managed centrally (e.g., through the NSW Soil and Land Information System, SALIS) for maximum utility and availability.

9.3 Key indicators

Provisional key indicators which would provide a solid evidence basis for forest and soil condition and stability include the following:

- Total organic C[1]
- pH[3]
- EC
- CEC[2]
- Texture[2]
- Total P[3]
- Total N[1]
- Bulk density[4]
- Aggregate stability[4].

[1]—prediction using MIR spectrometry
[2]—developing prediction using MIR spectrometry
[3]—potential for developing prediction using MIR spectrometry
[4]—potentially predictable using novel indicator(s) and/or pedotransfer function(s), but more research is required in Australian conditions.

As can be seen, a majority of these tests (6 out of 8) can be predicted using MIR spectroscopy, although some of these predictions are still under development (M Veeragathipillai pers. comm.). There remains the requirement for a proportion (~20%) of samples to be conventionally tested to ensure continuing accuracy of the MIR predictions.

The costs of data collection through MIR spectroscopy are comparable to that of traditional laboratory analysis. DPIE's Yanco laboratory indicates that costs of analysis for MIR measures are between half and one-third that of equivalent traditional analysis for total organic C and total N. Carbon fraction analysis is currently offered by the laboratory at less than 2% of the cost of carbon fraction analysis using traditional methodology.

Additionally, experience with MIR spectroscopy at DPIE's Yanco laboratory indicates that MIR predictions of C content become less accurate as organic C increases to very high levels, mainly due to a lack of forest soils in local calibration models. There is a need for further analysis of high-C forest soils using traditional techniques combined with C^{13} nuclear magnetic resonance (NMR) testing, a specialised technique that assesses the composition, structure and stage of decomposition of soil organic matter (Clemente *et al.* 2012). This will allow MIR predictions to be more accurate in forest settings.

This minimal dataset should allow important co-indicators to be predicted to be accurately predicted using pedotransfer functions (PTFs), as has been demonstrated by several studies. There is potential for this set to be further refined—e.g.: bulk density has been predicted by a number of studies, such as Al-Shammary *et al*. (2018), Beutler *et al*. (2017), Makovnikova *et al*. (2017) and Sequeira *et al*.

(2014); aggregate stability has been predicted by Rivera and Bonilla (2020); and other predictions are under development. These predictions, however, need to be localised to Australian forest soil conditions and rigorously tested and calibrated before being used.

9.4 Additional indicators

A provisional set of more comprehensive indicators to be collected at reference sites, beyond those above, are as follows:

- Soil organic carbon fractions can indicate a range of processes and changes, and may be more useful than total C. These fractions can be determined using MIR.
- Macro nutrients:
  - Ammonium (NH_4^+)
  - Nitrate (NO_3^-)
  - Total S
- Soil metagenomics: significant indicator of soil biological diversity.

9.5 Optional indicators

- **Folial nutrient analysis:** measure of nutrient uptake by plants
- **Folial nutrient analysis:** measure of nutrient uptake by plants
- **Heavy metals and other contaminants**: may be required in areas previously disturbed by industrial land uses, such as mining or minerals processing.

9.6 Soil quality index

An SQI for NSW forest soils could be developed by indexing and combining the above indicators to produce a single number for comparative assessment of soil health. Whilst not directly applicable for management action, an SQI may provide an instant indication of a soil's relative health and condition. However, as observed by Bünemann *et al.* (2018), an overall soil quality index is often desired, but soil quality is best assessed in relation to specific soil functions.

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