Forest Owners Association

SFF Milestone 1a
Soil Quality Indicators For Forest Condition Monitoring

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EXECUTIVE SUMMARY

The New Zealand Forest Owners Association (NZFOA) is committed to measures to maintain and improve forest condition. The need to consider the forest condition is a requirement at a number of management scales including; forest (Principles for Commercial Forest management in NZ, Forest Stewardship Council); regional (Resource Management Act); national (State of the Environmment); and international (Montreal Process and Santiago Declaration, Forest Stewardship Council). This report forms part of a project funded by the Sustainable Farming Fund (SFF) which examines measures of sustainability and productivity of New Zealand Forests. This report corresponds to Milestone 1a of the SFF proposal which states:

Milestone 1a: Investigate soil sampling protocols and produce report recommending best option.

The stated objective of Milestone 1a is:

To identify meaningful soil parameters that can be measured and monitored over time to provide an indication of sustainability.

Sustainability refers to stability in production and profitability, while preventing environmental degradation (Larson and Pierce, 1994). Land-use sustainability is linked to soil quality, where assessment of soil quality involves measurement of soil physical, chemical and biological properties.

From a review of soil quality and forest productivity literature four soil quality indicators were identified as influenced by management of a forest site. They have been denoted as Tier 1 indicators, and are:

- Total C;
- Total N;
- C:N ratio; and
- Bulk density.

Other commonly measured soil quality indicators were determined to be either too strongly influenced by site specific factors such as topography and climate; were suggested to be of limited value for the prediction of long term impacts on sustainability; or, were adequately predicted from the Tier 1 indicators or from foliar testing. However, the inclusion of additional soil quality indicators may be necessary in consideration of site specific factors. In addition to the Tier 1 indicators, a number of additional soil quality indicators are proposed for consideration on a site-by-site basis. They are denoted as tier 2 indicators, and are:

- Mineralisable N;
- pH;
- Total and available P;
- Base saturation or CEC; and
- Particle size distribution and macroporosity.

A forest condition monitoring programme (FCMP) is developed as a mechanism to address this issue. The programme design is based on research based programmes presently in use in NZ. This allows multiple functions to be achieved from the sampling plots. Soil (including the forest floor) is sampled from a mapped 20 x 20 m plot to give:

- Organic soil (4 composite samples);
- Mineral soil (4 composite samples x 3 soil depths); and

- Bulk density ring samples (4 samples).

Results of the sample analysis are able to be compared against a benchmark site where one exists; or are used to identify trends in soil quality temporally at the monitoring site. Options for management of the collected data should be decided in consultation with NZFOA members. Potential options include:

- Individual company responsibility – data is collected and interpreted by the forest manager responsible for the site. The use of the data for the purpose of accreditation of product or similar is at the discretion of the forest owner/manager;
- NZFOA managed database – data collected is submitted to a database managed co-operatively within the NZFOA. The database can be used to develop interpretive tools for assessing sustainability;
- Independently managed database – data collected is submitted to an independent third party with the ability to interpret the data and can use the database to develop interpretive tools for assessing sustainability.

Adoption of a data collation system which enables the establishment of a soil quality database covering the edaphic and environmental zones of NZ forests is recommended. This will assist in the development of a soil quality index of sustainability.

A review of available literature identified a lack of published data linking soil quality to the sustainability of a forest operation at present. There is a growing database of soil quality information for NZ soils from systems such as the 500 Soil project and the LTSP2 programme. While insufficient information from the LTSP2 has been published to independently develop a soil quality model of sustainability for NZ forests, the data may be available upon application where funding comes from “public good” sources such as FRST.

The CMS project, which is funded by the Ministry for the Environment (MfE) has an extensive database of total C and bulk density data across a wide range of sites and land uses. If total N data was obtained for these sites there may be potential for development of a soil quality index incorporating the indicators proposed for the FCMP. The use of this data would enable the comparison of forested sites with undeveloped sites of similar characteristics, representing a benchmark of soil quality corresponding to sustainable land use.

Further investigation is required in this area. In particular, there are questions surrounding the value that a long-term FCMP would provide to foresters, beyond that research already undertaken or being undertaken. It is therefore important to suggest that the implementation of a FCMP system should be carefully weighed against the understanding that the meaning of the changes in forest condition are not known with absolute clarity, and may or may not help foresters, long term, to better manage their forests.

In the absence of a definitive model to describe the forest condition, the US (and subsequently Canada) and Australia have adopted approaches whereby any detectable change is considered to correspond to degradation of soil condition. However, it should be noted that this is a highly conservative approach in the absence of well defined relationships between forest condition and soil quality indicators, and is likely to be refined to specific limits as knowledge increases in this area. Due to the high degree of heterogeneity in forest soils the level at which variance corresponds to a statistically significant difference is high. According to the US LTSP research, in the case of most indicators a change of >15 % is necessary to detect a change in the measured soil indicators with confidence (Powers *et al.*, 2005). In Australia a change of between 15 and 30 % depending on the indicator, corresponds to a detectable change in a soil indicator. A management response may be triggered at this level of change, most likely comparing the change in the measured indicator with any corresponding change in the net productivity of the forest stand or increased monitoring. We note that a change of 15-30% is undoubtedly significant, but the impacts of such a change may be positive or negative, and are particularly specific to the indicator observed and the site and not the forest condition. Thus, such change may not necessarily indicate degradation of the forest condition, but would hopefully guide the forest manager in better understanding long-term trends in environmental change.

It is recommended that if it were implemented, an FCMP adopt a similar approach in the absence of well defined relationships to sustainability of land use in New Zealand forests. Any detectable change, meaning a change in any indicator of >15 % should trigger a monitoring response, and a higher state of alertness with respect to the forest condition. The sampling design is structured to include information from different phases of the crop rotation. Soil processes are likely to be affected by the differing phases of tree growth and management and so management responses should be based on trends in forest condition data, and not on single results.

1. INTRODUCTION

1.1 Background

The New Zealand Forest Owners Association (NZFOA) is committed to measures to maintain and improve forest condition over time. The need to consider the forest condition is an inherent, and sometimes explicit requirement at a number of management scales including; forest (Principles for Commercial Forest management in NZ, Forest Stewardship Council); regional (Resource Management Act); national (State of the Environmment); and international (Montreal Process and Santiago Declaration, Forest Stewardship Council). This paper forms part of a project funded by the Sustainable Farming Fund (SFF) which examines measures of sustainability and productivity of New Zealand Forests.

DWG have been engaged to produce a report corresponding to Milestone 1a of the SFF proposal which states:

Milestone 1a: Investigate soil sampling protocols and produce report recommending best option.

The stated objective of Milestone 1a is:

To identify meaningful soil parameters that can be measured and monitored over time to provide an indication of sustainability.

The report comprises two parts:

- A review of readily available scientific literature and a summary of international and national monitoring methods for understanding forest soil quality; and
- A recommended methodology for a forest soil condition monitoring programme for NZ forests.

1.2 Sustainability and Soil Quality

Sustainability refers to stability in production and profitability, while preventing environmental degradation (Larson and Pierce, 1994). Land-use sustainability is linked to soil quality, which is defined by Doran and Parkin (1994) as:

> *The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.*

Physical, chemical and biological properties interact to determine soil quality (Gregorich, 1996). Therefore a thorough assessment of soil quality involves measurement of soil physical, chemical and biological properties.

The concept of soil quality as an indicator of sustainability is widely recognised as important for the assessment and advancement of sustainable forest management (Schoenholtz *et al.*, 2000). Past and on-going site productivity research has greatly increased our understanding of those soil and site properties and processes that influence forest development, and those that are influenced by management.

1.3 Factors for Consideration in the use of Soil Quality Indicators

As indicated in Section 1.2, sustainability is related to land use and intensity. When considering the measurement of sustainability, indicators should be chosen that are appropriate to the soil functions and processes of the land use and its inherent intensity. Many soil quality monitoring programmes have been instituted world-wide that are based on agricultural management systems. Significant differences in the soil properties and processes between agricultural soils and forest soils exist. A summary comparison between agricultural soils and forest soils is given in Table 1.

Table 1: Differences between agricultural and forest soils (after Moffat and Kennedy, 2002)

Agricultural Soil	**Forest Soil**
Topsoil often affected by cultivation; Ap horizon (this is an organic rich horizon whose formation is strongly influenced by cultivation) common.	More diverse humus forms; commonly well defined horizonation in topsoil.
pH usually >5.5	pH often <5.5
Small organic matter content	Large organic matter content
Moderate macroporosity	Large macroporosity
Relatively small spatial variability in many soil properties	Large spatial variability in many soil properties
Biological disturbance dominated by earthworms	Biological disturbance dominated by arthropods
Microbial biomass dominated by bacteria	Microbial biomass dominated by fungi
Relatively fertile	Relatively infertile
Relatively large diurnal variation in soil temperature	Smaller diurnal variation in soil temperature
Soils exploited by plant roots to moderate depth; soil drying accordingly	Soils exploited by tree roots to greater depth; soils maintained in drier state for longer period of year.

Unlike agronomic systems which give soil productivity primary importance in consideration of sustainability, foresters have historically considered soil as a component part of the whole forest unit as opposed to a separate resource in its own right (Schoenholtz *et al.*, 2000). More recently the concept of soil quality has been examined with regard to forest condition monitoring (Burger and Kelting, 1999; Watt *et al.*, 2005; Armacher, 2007; Moffat and Kennedy, 2002; Alianiello *et al.*, 2002; Rab, 1999). However, the concept of site quality incorporating climate, geologic, and topographic factors as well as soil and plant systems, is well understood and widely used by foresters (Schoenholtz *et al.*, 2000).

Determining forest soil sustainability must also take into account temporal factors. Typically a crop rotation lasts no less than 25 years. This is far in excess of cropping or pastoral rotations in agricultural soils. The phases of the forest management cycle (site preparation, planting, harvesting, etc) create separate and sometimes substantial soil disturbance, which must be accounted for in determination of sustainability of land use. Technological advances have enhanced long term crop yields, however the intensity of resource use due to these advances may have the potential to mask underlying declines in site productivity, and therefore sustainability, where crop yields are used as a sole indicator to describe productivity (Vance, 2000).

In a review of the state of knowledge into the use of soil quality indicators for forestry Moffat and Kennedy (2002) concluded that:

- Considerable understanding has been gained in conceptual development of soil quality in forests, while less focus has been directed towards how such systems work in practice;
- There is limited information regarding the costs and benefits of soil quality monitoring;
- Thresholds are largely deductive, with little research linking them to productivity;

- Site specific information must be taken into account in the interpretation of soil quality impacts on sustainability; and
- Considerable research is required to establish meaningful soil quality thresholds, and it is debatable whether the value of such thresholds would be sufficient to warrant the research required.

1.3.1 Relationship of Global Knowledge to the New Zealand Context

In consideration of a soil based programme of sampling for monitoring sustainability of NZ forests, a review of soil monitoring programmes in use in New Zealand and around the world should be undertaken. Particular emphasis should be placed on programmes focussed on forest sites.

While many of the fundamental issues influencing site sustainability are the same for all forest regions, some issues are region specific. For example, in areas with a long or intensive history of industrialisation particularly Europe and UK under the Helsinki Agreement, acidification and sulphur deposition is of concern when gauging the sustainability of forest sites. However, sulphur deposition and acidification due to atmospheric pollution from industry is not a significant contributor to the soil/atmosphere system in NZ. A soil quality monitoring programme requires assessment against the needs and challenges of NZ forestry.

New Zealand forestry differs from northern hemisphere forestry in that almost the entire forest industry in NZ is based on plantation production of exotic species. The management of indigenous old growth forests for wood production comprises a very small percentage of the forest harvest. New Zealand's exotic plantations are significantly altered ecosystems. This will influence the definition of a baseline state of soil quality.

2. SOIL QUALITY INDICATORS

Many definitions of soil quality have been proposed. Most incorporate the concepts of sustainability described in Section 1.2 (Schoenholtz *et al.*, 2000; Doran and Parkin, 1994; Kelting *et al.*, 1999). In order to quantify soil quality a set of indicators of soil quality must be defined in the New Zealand context.

A complete assessment of soil quality involves measurement of soil physical, chemical and biological properties. A 1996 Ministry of Agriculture research program identified a range of soil quality indicators (SQI) (Table 2). Soil physical indicators of soil quality indicate processes such as compaction and erosion. Soil chemical indicators of soil quality are often measured as part of a routine soil fertility test, and indicate the availability of nutrients for plant growth. Soil biological indicators are early and sensitive indicators of soil quality changes. It is important to ensure, though, that the indicators chosen have a direct and quantifiable link to soil quality for the majority of environments throughout New Zealand.

Like agronomic systems, plantation forestry is a managed ecosystem, however unlike agricultural management intervention is generally minimised. Soil quality goals for forestry must take into account the impacts of forest management. Forest soil quality is expressed in terms of tree growth or biomass production. However, other soil functions must be considered in a description of soil quality (Schoenholtz *et al.*, 2000; Smith *et al.* 2000). Other soil functions may include regulating water quality and quantity, carbon sequestration, remediation of human and animal wastes, regulating energy flow (Schoenholtz *et al.*, 2000) and socio-economic benefits (Smith *et al.*, 2000).

2.1 Criteria for Soil Quality Indicators

Indices of forest soil quality which incorporate soil chemical, physical and biological properties will be most readily adopted if they are sensitive to management-induced changes, easily measured, relevant across sites or over time, inexpensive, closely linked to measurement of desired values, and adaptable for specific ecosystems (Schoenholtz *et al.*, 2000; Larson and Pierce, 1994).

2.2 Measuring Soil Quality

The measurement of soil quality can be used as a proxy measure for forest condition when other variables are adequately understood. Forest condition is a point-in-time measure which can be used for management decisions. This should not be confused with sustainability which is a measure of longer term potential for maintaining productivity of a site without degradation of the environment. Soil quality does not account for variations in productivity due to climate and geological setting, or species selection, however the inherent soil quality of a site is influenced by these variables. Watt *et al.* (2005) attributed between 15 and 50 fold variation in volume increment to site factors, and 56 % difference due to species. It should be noted that the inherent soil quality of a site is unlikely to be that of an ideal soil, where “ideal” indicates that no limitations to biological productivity, environmental quality or plant and animal health exist. This is especially true for forest soils since forest is typically established on marginal sites as described in Section 1.3.

In simple terms the maintenance of soil quality, and therefore the sustainability, at a site means that if all management inputs ceased the site would be able to support the ecosystem and vegetative cover that existed prior to forest establishment. In some situations forest has been established on sites previously degraded by inappropriate or exploitative land use management e.g. land damaged by erosion caused by pastoral farming on inappropriate slopes. In this case the establishment of forest might be considered as a remediative measure and the goal should be improvement of soil quality from the level exhibited prior to forest establishment e.g. through slope stabilisation, build-up of soil C and N stocks, etc.

An evaluation of the use of bioassays for assessment of the effect of management on soil productivity by Burger (1996) demonstrated that tree growth could not always be used to measure management-induced productivity changes. It has been proposed (Burger, 1996; Kelting *et al.*, 1999) that long-term site productivity (LTSP) should be assessed by direct measurement of soil properties and processes.

When used together with mensuration and foliar nutrition information, measurements of soil properties and processes, allow detection in changes in the ecosystem resulting from different management systems (Périé and Munson, 2000). There are limitations to testing for each of physical, microbiological and chemical soil parameters which can help us to refine the testing programme.

2.2.1 Minimum Data Sets

The use of a minimum data set for soil quality assessment to minimise complexity and cost is important to encourage the adoption of the approach by practitioners (Kelting *et al.*, 1999). A minimum data set for characterisation of soil under any management was proposed by Doran and Parkin (1994). Numerous other minimum data sets have been proposed which are based on the indicators listed in Table 2. The minimum data set can be further refined to ensure its relevance to forest condition monitoring.

Table 2: Soil Quality Indicators (after Doran and Parkin, 1994)

Indicator	**Measurement**
Physical	
Aggregate size and stability	Visual description in field or sieving techniques in laboratory.
Texture	Field feel tests or laboratory analyses by laser particle sizer or sieving.
Hydraulic conductivity	A variety of methods such as twin rings and permeameters.
Water holding capacity	Derived from measured physical properties.
Bulk density	Field measurement by gamma density probe. Laboratory analysis using soil cores.
Penetration resistance	Field measurement by penetrometer.
Chemical	
pH	Laboratory measurement using pH electrode.
Nutrient status	Total N, mineral N, available P and K in particular, measured.
Nutrient Budget	Measured over several years.
Cation exchange capacity	Laboratory analysis using leaching columns or silver thiourea extraction are most common.
Biological	
Microbial biomass	Most often laboratory or *in-situ* analysis by fumigation-extraction or fumigation-incubation methods.
Potentially mineralisable N	Laboratory or *in-situ* analysis by anaerobic incubation.
Microbial quotient	Derived from microbial biomass C and soil organic C.
Soil respiration	Laboratory or *in-situ* measurement of CO_2 respired or O_2 consumed.
Metabolic quotient	Derived from microbial biomass C and soil respiration.
Soil fauna	Usually earthworms. The number and type of earthworms are given.

2.2.2 Soil Physical Parameters

Physical indicators of soil quality indicate processes such as compaction and erosion (Gregorich, 1996). Forest management practices particularly relating to site preparation and harvesting practices are well understood to impact the soil physical properties of a site and extensive study aimed at quantifying the impacts has been undertaken.

Grigal (2000) placed high importance on the alteration of soil physical properties as an indicator of management-induced change in soil quality. Soil physical changes are of particular concern as they are of relatively long duration, of high certainty and are not easily repaired (Grigal, 2000). They have significant and well-documented negative effects on productivity (Tan *et al.*, 2006; Murphy *et al.*, 2004). Conversely, some studies have identified that changes to soil physical properties have a negligible or temporary effect on productivity (Sanchez *et al.*, 2006; Hope, 2007; Powers *et al.*, 2005).

Some soil physical parameters are related to soil formation and are unlikely to be effected significantly by land use and management practices. Soil texture or particle size distribution (PSD) is a fundamental soil physical property which influences water, nutrient and oxygen exchange, retention and uptake (Schoenholtz *et al.*, 2000). Schipper and Sparling (2000) showed that land use had little to no impact on PSD unless substantial mixing of soil horizons (i.e. by logging operations) had occurred. PSD is an inherent property of a soil and does not change with land use. Because this measure is not sensitive to land use change and is not a function of soil condition it has limited value as a SQI for monitoring. PSD may be valuable for characterising soil at the outset of a change in land-use (Schoenholtz *et al.*, 2000). Powers *et al.* (2005) demonstrated that PSD influenced the effect of increased bulk density on tree growth, indicating that more than one soil property should be taken into consideration in assessment of the soil quality.

Soil depth is fundamental to a site's productivity as it controls the amount of resources and the volume available for rooting. Changes in soil depth occur due to erosion processes, soil compaction and some management practices which cause bulk movement or removal of soil and litter layers. It has been suggested that depth of the A horizon (topsoil) should be included in SQI for site sustainability (Watt *et al.*, 2005). In a short term, high density site productivity trial representing a wide range of NZ soils and environmental conditions, Watt *et al.* (2005) found that depth of the A horizon was correlated with volume increment in *P. radiata* and *C. lusitanica* stands. Schoenholtz *et al.* (2000) suggest that soil quality issues related to horizon depth can be adequately predicted from measurement of bulk density. Watt *et al.* (2005) found that macroporosity and cone penetration resistance were not strongly related to increment reductions, whereas bulk density showed correlations with volume increment.

Changes in soil bulk density occur due to a range of management related activities. Typically an increase in bulk density may indicate erosion processes exposing mineral soil horizons or (more often) compaction. Change in soil material composition i.e. through addition or removal of organic material can cause either an increase or decrease in soil bulk density. Bulk density varies widely between soil types, and so is best considered as a temporal monitor of management-induced changes within a site (Schoenholtz *et al.*, 2000). However, Powers *et al.* (1998) suggests soil strength as measured by cone penetrometer may be the best way to index the influence of density on root exploration, proliferation and growth.

Many authors favour the inclusion of bulk density in the minimum data set of SQIs since it is related to many other soil physical parameters i.e. macroporosity, soil texture, water holding capacity. The soil bulk density is likely to be a useful indicator of long term site productivity since it has been seen to recover from pre-plant compaction during a crop rotation (Sanchez *et al.*, 2006; Hope, 2007). This suggests that it is a good indicator of long term or irreversible degradation of soil quality at a site. In addition, bulk density measurement enables the conversion of soil chemical concentrations to a mass per unit area basis. Expressing soil chemical concentration on a mass per unit area basis has been shown to account for a large amount of variation in chemical indicators where bulk density change at a site has occurred.

Soil water interactions are important to soil quality, however they can often be inferred from indirect measures such as bulk density. There are few measures of soil moisture status and water holding capacity that are simple and inexpensive to perform.

2.2.3 Soil Chemical Parameters

Chemical indicators of soil quality are often measured as part of a routine soil fertility test, and indicate the availability of nutrients for plant growth (Gregorich, 1996). The measurement of soil nutrient status of agricultural soils has been widely adopted as a measure of soil quality. For forestry soils, nutrients have been incorporated into intensive site monitoring and research programmes. Due to long crop rotations and complex nutrient cycling mechanisms within the forest ecosystem, nutrient testing of soils may not be a good indicator of sustainability of forest soils (Schoenholtz *et al.*,2000).

The use of chemical indicators of soil quality has been given varying importance in reviews. Grigal (2005) states, that except on a few exceptional sites, nutrient loss is not a major concern. And further, that effects of nutrient deficiency are long term and likely to take more than one rotation to occur, allowing adequate time for diagnosis and amelioration of the deficiency. Moffat and Kennedy (2002) suggest that foliar testing may serve as sensible surrogates of soil chemical status in forest soils. Foliar testing directly reflects plant uptake, which is integrated across soil horizons. Indeed NZ forestry has long used foliar testing as the key decision variable with respect to the use of fertilisers to overcome nutrient deficiencies.

Nutrient imbalances can be detected with greater sensitivity through foliar testing which can be directly correlated with plant growth. Foliar testing has none of the uncertainty associated with soil testing (e.g. relating forms and availability of nutrients to plant uptake). Testing methods for foliar nutrition are well established, reliable and significant historical data is held for many New Zealand sites. In addition, foliar testing is generally undertaken at two to four yearly intervals, allowing for comparatively rapid assessment of a change in the nutrient status of the stand.

However, the use of soil chemical indicators for monitoring of forest soil quality and site sustainability is commonly recommended (Schoenholtz *et al.* 2000; Burger and Kelting, 1998; Powers *et al.*, 1998; Watt *et al.*, 2005; Armacher *et al.*, 2007).

Any given soil property may be relevant to several soil attributes or soil functions simultaneously. An example of this is soil organic matter (SOM), which plays a role in almost every soil function. Also, many soil chemical properties directly influence microbiological processes, and these processes together with soil physical-chemical processes determine (1) the capacity of the soil to hold supply and cycle nutrients , and (2) the movement and availability of water (Schoenholtz *et al.*, 2000). Soil chemical indicators are used mostly in the context of nutrient relations and may therefore also be referred to as indices of nutrient supply (Schoenholtz *et al.*, 2000, Powers *et al.*, 1998).

Soil chemical properties can be divided into two categories: Static and dynamic soil parameters. Static soil parameters are measures which describe fundamental soil properties that do not change substantially over time; and dynamic soil parameters which are soil process related. Static soil parameters are typically simple and practical to measure, however they are hierarchically several levels removed from the soil function. The dynamic process measures are more directly related to the soil function, however are typically more laborious and costly to measure (Schoenholtz *et al.*, 2000). In addition, dynamic parameters may not reflect long term changes in site sustainability. In describing soil quality relating to long term sustainability a balance must be struck between soil properties which are not influenced by short term perturbations unrelated to sustainability of the land use, but may be insensitive to changes in ecosystem function; and soil processes which are closely related to ecosystem function and plant uptake, but may be too variable both spatially and temporally to provide clear trends in soil quality.

A discussion of commonly prescribed soil chemical parameters is given below.

2.2.3.1 pH

pH refers to the hydrogen ion activity of the soil. The more acidic a soil, the lower its pH. In NZ, forest soils are typically acidic due to the soil forming factors at the site. Tree species grown on forest soils are typically adapted to growing in low pH soils, and this may be a contributing factor to the selection of a site for forestry.

Both, management induced and natural processes can lead to changes in the soil pH. Fertilisation of sites occurs in most NZ forests. Fertilisers such as superphosphate, urea and DAP cause acidification. Decomposition of litter also increases the soil acidity. The ability of the soil to regulate pH following addition of low pH inputs is its buffering capacity. Soils with a low buffering capacity are more susceptible to loss of productive capacity. Forest species are grown on sites with pH as low as 3.6 without severe limitation to productivity. However, as pH reduces soil aluminium is mobilised and will eventually cause toxicity effects. In addition, at low pH calcium becomes unavailable and nutrient deficiencies may occur. Ca/Al ratio may be a more sensitive measure of toxic effects from soil acidification which may be detrimental to soil quality.

Many chemical reactions that influence nutrient availability are influenced by soil pH. Measurement of soil pH has been widely performed in historical studies and the testing methods are well understood, and easily and inexpensively conducted. For these reasons pH may be considered as a key chemical indicator.

However, because pH influences so many biological and chemical functions of the soil simultaneously it provides little direct information about affected soil processes, and in turn the impact of changes to pH on the productive capacity of the soil. Aune and Lal (1997) suggested that pH may not be a sensitive measure of soil acidity and soil degradation.

2.2.3.2 Soil Carbon and Soil Organic Matter (SOM)

Soil organic matter (SOM) includes all carbon compounds in soil associated with biological activity (excludes carbonate bound carbon) and contains a number of other elements including nitrogen, phosphorus, sulphur, cations and trace elements. Typically carbon comprises approximately 58 % of SOM, however this can vary according to the composition.

The distribution and composition of SOM in forest soils differs from that typically observed in agronomic soils which are subject to frequent mixing, causing homogenisation and respiration of accumulated carbon. Forest SOM pools are dominated by the accumulation of litter from trees. The forest soil represents a gradient in degree of SOM decomposition, with incorporation of carbon into the mineral soil through leaching of organic acids derived from the breakdown of litter and roots, and bioturbation (i.e. mixing by animals such as worms and burrowing animals). SOM in forest soils varies widely in composition due to varying degrees of decomposition of the accumulating litter layer and movement of organic compounds through the soil.

SOM has an important role in forest soil processes. SOM is important for nutrient availability, soil structure, air and water infiltration, water retention, erosion prevention and the transport or immobilisation of pollutants (Knoepp *et al.*, 2000). SOM is commonly recognised as one of the key chemical parameters of soil quality, yet quantitative assessment of its contribution to soil quality is often lacking (Schoenholtz *et al.*, 2000). Defining quantitative criteria for

SOM is further hampered by the fact that critical threshold values may be vastly different among soil orders, climatic regions and land use/species composition (Doran and Parkin, 1996; Burger,1997; Burger and Kelting, 1998).

SOM is related to most chemical and many biological variables in forest soils (Prévost, 2004). However measurement of SOM alone does not correlate directly with other soil functions (Schoenholtz *et al.*, 2000). Long term soil productivity (LTSP) trials established in NZ (Murphy *et al.*, 2004), the US (Sanchez *et al.*, 2006) and Canada (Hope, 2007) have not shown reductions in tree growth on sites with varying degrees of SOM removal prior to planting. In the US study the removal of SOM had impacted the phosphorus status of the soil, but after 10 years no impact on tree growth had been detected.

SOM is easily and inexpensively measured, however it is unlikely to be a sensitive measure of changes in soil quality. More sensitive information can be obtained from the measurement of the components of SOM e.g. carbon, nitrogen, etc, and their relationship to each other e.g. C:N ratio.

The most dynamic soil C pool is in the forest floor. Due to high rates of turnover in the forest floor, this C pool is subject to short term variation influenced by climate, stand age etc. Organic matter cycling in the mineral soil layers is typically slower and less sensitive to short term changes. A long term decline in soil C will be more easily distinguished in the mineral soil.

Johnson and Crossley (2002) state that a long-term perspective on soil fertility shifts the focus from litter dynamics to more persistent types of organic matter such as roots, coarse woody debris and humus. High spatial variation makes difficult to distinguish whether variations in organic matter in the forest floor are due to changes over time or due to management (Yanai *et al.*, 2000). Hopmans *et al.* (2005) consider that the > 2 mm soil fraction should be included in measurement of soil carbon pools. The > 2 mm fraction has an impact on site sustainability when considered in the long term due to the breakdown of coarse woody debris and the effects of *insitu* breakdown on soil porosity.

Bauhus *et al.* (2002) found relationships between soil organic C (SOC) and organic matter quality and N and P availability were inconsistent across sites in native eucalypt sites in Australia, and between different management practices. This may be attributable to the amount of charcoal present in the soil. It was further stated that changes in SOC cannot be recommended for implementation as an indicator of sustainable soil management in native eucalypt forests since there is no evidence that SOC is limiting to ecosystem processes. In addition the measurement of SOC remains the task of experts causing testing to be expensive and not widely available.

There has been extensive study into the relationships between SOM and soil carbon with the forest ecosystem. Testing for SOM and total C is well established and widely available by dry and wet combustion methods. For NZ soils there is little free carbonate in topsoils and total C is in nearly all cases equivalent to organic C. In addition, organic C comprises a constant proportion of SOM and so for NZ soils total C is considered to be an acceptable measure of organic matter.

2.2.3.3 Total and Available Nitrogen

Nitrogen (N) is a key macronutrient used in plant and microbial growth and reproduction. The majority soil N is complexed in SOM (O'Neill *et al.*, 2005) and is unavailable to plants until it is mineralised by soil microbes.

Forest soil scientists are frequently interested in the measurement of soil total C and N as these are generally considered to most strongly influence the long-term fertility of a site (Johnson and Curtis, 2001). A large pool of N in the surface soil is considered important for site productivity (Page-Dumroese, 2000). For longer term site productivity of some sites, N and C at greater depth becomes an important indicator of historical and thus future productivity (Henderson, 1995). In soils with a significant charcoal content soil N is a better indicator of soil quality and sustainability than soil C (Hopmans *et al.*, 2005). Thus the type of C in the soil, relative to N, and its origins are also a factor in productivity.

Total N in New Zealand soils is typically comprised of 95-98 % organic N (McLaren and Cameron, 1991). The organic N fraction is not readily available for plant growth however, it is likely that the organic N fraction has a significant impact on the supply of N for tree growth and ecosystem processes over the course of a single or of multiple rotations as it becomes progressively mineralised into the available N fraction.

The available nitrogen fraction of the soil represents the potential immediately available supply of N for the crop. Due to the length of single and multiple rotations rotations being incompatible with the rapidity of mineralisation of N in soils it is likely that the total N pool in the soil is a more appropriate indicator N supply sustainability for plant growth and ecosystem processes. However, the ability of the crop to utilise N is a function of the total N plus the ability of the soil to mineralise N over time. A measure of this is mineralisable N. Therefore, readily mineralisable N becomes a key component in the overall picture of year-on-year nutrient supply, which lends to long term productivity.

Mineralisable N has been proposed as a SQI by a number of authors (Knoepp *et al.*, 2000; Powers *et al.*, 1998; Mariani *et al.*, 2006; Doran and Parkin, 1994). Mineralisable N is a measure of N availability and N supplying capacity of soil (Schoenholtz *et al.*, 2000). A number of methods for measuring mineralisable N exist, both as chemical assays and as microbiological methods such as incubation-extraction. Mineralisable N is closely related to biological soil function and highly correlated with other measures of nutrient release (e.g. soil C:N, total organic C and N, P mineralisation, site index, foliar N) (Schoenholtz *et al.*, 2000). It has been shown to be very sensitive to seasonal variation and may not be well correlated with long term sustainability (Perie, 2003). Until recently testing for mineralisable N has been relatively expert and not widely available in NZ. The test is now available at a commercial laboratory relatively inexpensively. Care must be taken, however, to indicate the testing method when this test is reported, as the relationship between different measures is not well correlated, thus it is best to use one method. The predictive value of this indicator may be lost in systems where N is not the main growth limiting factor (Schoenholtz *et al.*, 2000).

Powers *et al.* (2005) demonstrated that organic matter removal had a significant and substantial effect on total, anaerobic and KCl extractable N. Another factor to consider is the spatially heterogeneous nature of both organic matter and corresponding N pools within a forest ecosystem, particularly a managed system. This, coupled with the temporal changes in both pools over the length of a rotation suggest that to be well understood, these values require measurement over the length of several rotations.

2.2.3.4 Carbon to Nitrogen Ratio

The ratio of organic C to N is frequently used as an indicator of litter quality (O'Neill *et al.*, 2005). The ratio of C:N in organic matter is typically a function of the degree of decomposition and therefore stability of the organic matter pool. As decomposition of organic matter occurs CO_2 is released to the atmosphere and the C:N ratio decreases. As the C:N ratio decreases mineralisation of nitrogen increases which is subsequently available for plant uptake.

C:N ratio is not as widely employed as other soil quality indicators, however it provides an index of the rate of nitrogen mineralisation, and has been used to model growth (Watt *et al.*, 2005).

The influence of C:N ratio on the soil is in the control of nutrient cycling. Care must be taken with the use of C:N ratios, however, as they are generally acknowledged to provide only a crude estimation of the ability of a soil to store and mineralise N, and the forms of C inherent in the forest floor and surface soils may have a large impact on the actual storage capacity of these nutrient pools. Further refinements of the C:N ratio have been studied, including relating N to cellulose, lignin or other labile components of the C fraction, with varying degrees of success.

2.2.3.5 Total and Available Soil Cations and Trace Elements

Cations (Ca, Mg, K and Na) as well as trace elements bound to the soil are the predominant supply of these nutrients to plants. Clay minerals are the largest pool of these nutrients, however most of the clay bound nutrients are unavailable for plant uptake. Measurement of total elemental concentrations has little correlation with the soil quality and ongoing productivity of a site. A survey of forested soils in Europe demonstrated that soil texture largely determined the supply of cationic nutrients (Vanmechelen *et al.*, 1997)

Exchangeable cations correspond to the fraction of plant available nutrients. Nutrients held in this fraction are adsorbed to clay mineral edges and soil organic matter. Changes in soil chemistry cause exchangeable cations and trace elements to be released into soil solution for plant uptake and microbial processes.

While the role of these nutrients in plant growth is well understood, the relationship of plant uptake to soil supply is not well defined. Quantitative information regarding cation cycling in forest soils is limited. McLaughlin and Phillips (2006) demonstrated that exchangeable cations in a 17 year old stand of red spruce and balsam fir were not depleted by whole tree harvesting at the site prior to planting of the stand. In NZ site quality plots exchangeable cations (calcium, magnesium, potassium and sodium) were not influenced by site disturbance (Watt *et al.*, 2005).

A number of authors have proposed molar Ca/Al ratios (Cronan and Grigal, 1995) as an ecological indicator of potential nutritional stress. As Ca is depleted by tree uptake and removal, Al base saturation increases to potentially toxic levels with corresponding impacts on ecosystem health. Ca/Al molar ratios are not extensively used as chemical indicators because of the limited extent of the problem. Additionally, the testing required is specialised (i.e. not widely able to be reliably measured) and expensive.

The use of soil cation status as a SQI is not recommended due to lack of correlation to measures of site sustainability. Foliar testing for calcium, magnesium, potassium and trace elements are routinely undertaken for NZ forest sites. It is considered that foliar testing is a more direct and sensitive measure of the stand nutrient status.

2.2.3.6 Soil Cation Exchange Capacity (CEC) and Base Saturation (BS)

The soil CEC is an indication of the soils capacity for storage and release of nutrients and trace metals. Clay minerals and organic matter typically have a net negative charge which means that negatively charged exchange sites of these particles can adsorb positively charged ions (cations) such as Ca^{2+}, K^+, Mg^+, Na^+, NH_4^+ and trace metals. As soil chemistry changes adsorbed cations are bound or released into the soil solution for plant uptake and microbial processes. The proportion of available sites for adsorbing cations that are occupied is the percent base saturation.

The soil CEC is highly dependent on the balance of H^+ ions in the soil and so is influenced by pH. In NZ the widely available testing method for CEC involves a buffered extractant solution which causes CEC of acidic soils to be substantially overestimated. Unbuffered extracts are available but typically require a higher degree of expertise and are correspondingly more expensive.

Quantitative information on CEC in forest soils and in particular the contribution of forest floor layers to the soil CEC is lacking (Page-Dumroese *et al.*, 2000). Aune and Lal (1997) found that for acidic ultisols and oxisols, CEC is less important to the soils nutrient supplying capacity than the percent base saturation. This indicates that in soils that are naturally more extensively leached (i.e. under acid forming mor) the composition of the exchange complex is more important than the soil CEC. Because soil acidification is naturally occurring under forested sites, base saturation has a greater influence on soil solution chemistry and acidity and is a more useful indicator of the impact of soil acidification on site sustainability.

CEC in forestry soils is related mostly to the soil C (Page-Dumroese *et al.*, 2000). As a SQI for forest soil CEC should be considered as a second tier measurement in the event that soil C has indicated that soil quality had deteriorated.

2.2.3.7 Soil Phosphorus

Phosphorus has an important role in forest ecosystems, influencing most biological processes and impacting plant growth. Frequently soil P is bound in forms that are unavailable for plant uptake and P may become a limiting factor for site productivity (O'Neill *et al.*, 2005). This effect is particularly important for soils containing short range order clay minerals such as allophane. These soils occur extensively in New Zealand forest estates, particularly in the central North Island.

Mineral P in the soil is derived from apatite group minerals in the soil parent material. The contribution of mineral P to the labile P fraction is dependent on the degree of weathering of the soil. In climatic zones where soils have been subject to extensive chemical weathering such as Northland, if apatite minerals are present in the parent material it is likely mineral P has a significant impact of the available P of the soil. Similarly in areas subject to high rates of physical weathering such as in areas previously subject to glaciations in the South Island mineral P may contribute to the available P fraction. However in areas where soils are comparatively young and unaltered the mineral P fraction is non-labile and may not contribute significantly to the available P fraction. Where there is a significant unaltered mineral P content in a soil, the measurement of total P may overestimate the ability of the soil to supply P for tree growth and ecosystem processes.

Organically bound P content in New Zealand soils varies widely from 20-80 % of the total P of the soil (McLaren and Cameron, 1991). It is likely that the organic P fraction has a significant impact on the supply of P for tree growth and ecosystem processes over the course of a single or of multiple rotations as it becomes progressively incorporated in to the available P fraction.

The use of total P as an indicator of soil quality and therefore sustainability should take into account the soil parent material, degree of weathering and contribution of organically bound P to the total P pool. Due to the reliance of total P on many non-management induced variables, it may not be a useful indicator of sustainability.

It has been observed that total P in forest soils is correlated with soil organic C content. An increase or decrease in organic C was seen to be directly correlated to total P in forest soils (Périé and Munson, 2000). On soils with low P status, soil available P was negatively influenced by OM removal (Sanchez *et al.*. 2006). Measurement of soil P (available or total) may be warranted where a significant reduction in organic matter occurs on a site. Foliar testing is likely to adequately describe the P status of the site. However, where a significant reduction in soil C is measured, available P may be recommended for inclusion in the sampling regime.

Available P in the soil is present as phosphate. The available P fraction describes the immediately available P in the soil. In agronomic systems available P measured by the Olsen P method is frequently used as an index of productivity. Olsen P measures available

P at pH 8.5. The usefulness of Olsen P for describing forest soil condition is limited due to poor correlation between Olsen P and P availability for plant uptake. Alternative available P tests (Bray, Truog) are more appropriate for forest soils however they are not widely available. Furthermore, P status of the crop can be assessed more accurately by foliage testing.

Sparling *et al.* (2000) noted that for NZ soils, Olsen P values under plantation forestry are generally lower than other land uses. However insufficient information exists to determine whether depletion has occurred due to forestry. In addition, values representing critical limits for productivity and sustainability have not been established.

Available P may have limited value as an indicator of long term sustainability. Low P is typically ameliorated by the application of fertiliser. The alteration of the soil P pool by the added fertiliser has the potential to mask changes in the soil quality, suggesting it may be of limited value as an indicator of soil quality.

2.2.4 Soil Biological Parameters

Soil biological indicators are early and sensitive indicators of soil quality changes. Biological indices of soil quality yield evidence of how a soil functions and interacts with plants, animals and climate that compromise an ecosystem (Knoepp *et al.*, 2000). Many of the biological indicators relate to the cycling of soil organic matter. Often recommended biological indicators include: nitrogen mineralisation, microbial biomass, microbial biomass to total carbon ratio, soil respiration, respiration to microbial biomass ratios, faunal populations and rates of litter decomposition (Knoepp *et al.*, 2000; Sparling, 1997).

There is debate over the interpretation of soil microbial properties. For instance, population stress indicated by high respiration rate may just reflect the high C:N ratio typical of forest soil, or that ecosystem is young and is developing.

Microbial properties vary widely over both temporal and spatial scales. Climate and water supply has a large impact of the soil biological properties (Perie, 2003). Large variation is seen due to inhomogeneity of forest soils due to tree roots, preharvest site preparation (Ponder and Tadros, 2002; Li *et al.*, 2004).

2.3 Summary

There is little complete agreement about the nomination of soil quality indicators in the literature reviewed. This reflects limited information regarding the relationships between indicators and forest soil quality. In addition, conflicting relationships between soil properties and site productivity are often encountered in the literature.

It is widely acknowledged that soil physical properties are fundamental to soil quality. Commonly measured parameters include soil bulk density, soil or horizon depth, and soil water characteristics. Many of the physical properties are interrelated, enabling multiple properties to be inferred from one measurement. Soil bulk density is the most widely used physical parameter for soil quality measurement.

Soil chemical properties are related to both soil physical (e.g. organic matter influence on porosity, bulk density and water holding capacity) and biological properties. Nutrient status of forest soils are not well correlated to site sustainability and so have limited value as SQI. Soil pH is simple and inexpensive to measure however, it has been suggested that it is not a sensitive measure of soil degradation.

Soil organic matter is involved in most forest ecosystem processes. Changes over time may not be adequately detected by soil organic matter alone due to the complex and variable nature of the wide array of organic compounds that can be present in SOM. More information about the soil organic matter composition is needed. The measurement of total C, total N and total P gives additional information about the organic matter quality. The C:N ratio is a sensitive measure of changes to the soil organic matter pool and relates closely to ecosystem functioning.

Soil biological properties are sensitive measures of relatively rapid changes in soil quality. The interpretation of soil biological properties and their effects on forest condition and sustainability in forest soils is not well developed. Testing for most biological indicators is laborious and expensive, suggesting that they are not suitable for use as long-term SQI for forest soils.

3.0 SOIL QUALITY MONITORING PROGRAMMES IN USE

Many countries have instituted soil quality monitoring programmes to assess the sustainability of the soil resource in response to human induced pressures (Winder, 2003). Many programmes are designed to measure soil quality across land-uses. Most programmes are conducted at the national level and are managed by governmental organisations. A review of soil quality benchmarking programmes (Winder, 2003) identified 52 programmes in use across North America, Europe, NZ and networks (ICP, Pan-European, etc.). Of the 52 programmes 10 were identified as monitoring forest condition exclusively and a further 8 included forested ecosystems. A summary of the programmes identified is given in Table 3.

Table 3: Soil Quality Programmes with Forested Sites (modified from Winder, 2003)

Programme	Location	Forestry Only (FO) or Multiple Land Use (ML)	Soil Parameters Measured		
			Physical	**Chemical**	**Biological**
Long-Term Soil and Vegetation Plots Established in the Oils Sands Region	Alberta, Canada	FO	D_B, PSD.	pH, EC, $CaCO_3$, CEC.	None
Forest Health Monitoring Program (1990-1999) / Forest Inventory and Analysis Program (1999-present)	USA	FO	D_B, PSD, soil moisture, aggregate stability, penetration resistance	pH, EC, $CaCO_3$, Total C, TOC, Total N, CEC.	None
Forest Soil Monitoring System	Austria	FO	PSD	pH, $CaCO_3$, TOC, Total N, CEC.	None
National Soil Inventory	England and Wales	ML	PSD	pH, TOC, Total Na, K, Ca, P CEC.	None
National Forest Inventory	Finland	FO	Not reported	Not reported	Not reported
Soil Quality Observatory	France	ML	D_B, PSD.	pH, $CaCO_3$, TOC Total N, CEC.	N_{min}, C_{min}, mesofauna, enzyme activity
RENECOFOR	France	FO	None	TOC, Total N	None
Permanent Soil Monitoring Sites	Germany	ML	None	pH, exchangeable Ca, K, Mg, Na	Not stated.
Information and Monitoring System of Soil Conservation (TIM) – Special Areas Monitoring	Hungary	FO	Hydraulic conductivity, soil water characteristics, PSD	pH, EC, $CaCO_3$, Total C, TOC Total N, CEC.	Respiration
National Environmental Monitoring Programme – Forest Soil Monitoring	Lithuania	FO	None	pH, EC, $CaCO_3$, Total C, TOC Total N, CEC, Total Na, K, Ca, P,	None

				exchangeable acidity.	
National and Regional Soil Quality Monitoring Network	Netherlands	ML	PSA	pH, EC, TOC, Total K	None
National Program of Environment Monitoring	Poland	ML	D_B, PSD.	pH, $CaCO_3$, Total C, TOC, Total N, CEC.	none
Programme for Forest Monitoring	Poland	FO	None	P, K, SO_4, Ca, Mg, Na, NH_3, NH_4, NO_3	None
National Integrated Soil Monitoring System	Romania	ML	Not stated	Not stated	None
Slovak Environment Monitoring	Slovakia	ML	D_B, PSD, porosity, infiltration rate.	pH, EC, TOC, Total C, Total N, CEC, Total Mg, Total K, Total P, KCl	None
National Swedish Environmental Monitoring Programme - National Survey of Forest Soils and Vegetation	Sweden	ML	PSD	pH, CEC, Total C, Total N.	None
Swiss Soil Monitoring Network	Switzerland	ML	D_B, PSD.	pH CEC, aluminium oxide	None
Implementing Soil Quality Indicators for Land – “500 Soils Project”	New Zealand	ML	D_B, PSD, soil water characteristics, aggregate stability, porosity	pH, CEC, Total C, Total N, Olsen P	N_{min}, respiration, microbial biomass
International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests – ICP Forests level 1 & 2	United Nations Economic Commission for Europe	FO	None	pH, EC, $CaCO_3$, Total C, TOC, Total N, CEC, Total Na, K, Ca, Mg, P.	None
Environmental Change Network	United Kingdom	ML	D_B, PSD, soil water characteristics	pH, $CaCO_3$, Total inorganic C, TOC, Total N, CEC, Total P, Total S, exchangeable acidity.	Microbiological
Terrestrial Ecosystem Monitoring Sites	International	ML	D_B, PSD, soil water characteristics, infiltration.	pH, $CaCO_3$, Total C, TOC, Total N, CEC, Total P, exchangeable acidity.	Macrofauna, microfauna, microflora, respiration.

As a summary of the above table, it is noted that the most commonly measured parameters from these systems are the following:

- Soil Physical – Bulk density (D_B) and particle size distribution (PSD);
- Soil Chemical – pH, Total C or TOC, Total N, CEC and $CaCO_3$; and
- Soil Biological – Most frequently no biological indicators were measured.

The programmes listed in Table 3 exclude long term research plots and programmes which have not been resampled since the monitoring began. Some programmes of relevance to this review may be excluded on this basis. We highlight some of the relevant programmes below.

3.1 US Forest Service Long Term Site Productivity

Of particular relevance is the USDAs Long Term Soil Productivity (LTSP) experiment (Powers *et al.*, 2005). The experiment was strongly influenced by pioneering work at Maramarua Forest, NZ established in 1989 (Skinner *et al.*, 1989). The US LTSP was established in 1996 at sites representing the climatic and geological range of North American forests. The purpose of the US LTSP was to address the ultimate consequences of pulse soil disturbance on fundamental forest productivity.

The LTSP aimed to be persuasive to forestry professionals faced with day-to-day management decisions. This prompted an extensive review of the world literature (Powers *et al.*, 1998), which revealed that primarily two soil factors are affected by forest management operations. The soil factors were determined to be indicative of changes in two ecosystem properties most apt to impact long term productivity. The properties that were most influential to long term productivity are soil compaction due to long term cumulative impacts of mechanical site preparation as measured by porosity changes; and organic matter loss through biomass removal (Powers *et al.*, 1998). Results from the oldest plots are incorporated in the soil quality indicator review above.

It is considered that the aims of the USDA LTSP are well aligned to the objectives of the FOA. What is absent in the US LTSP program is an index of nutrient availability. While fertilisation based on foliar testing will provide adequate information for sustaining growth and growth rates, the ability of the soil to regulate nutrient supply becomes increasingly important after canopy closure when the forest system is reliant on a supply of endogenous organically bound nutrients (soil and litter cycling). The ability of the soil (microbial community) to mineralise organic material to release nutrients is fundamental to the site. Mineralisable N becomes an important measure. However, exactly how it relates to site productivity is not well established.

3.2 New Zealand 500 Soils Project

In New Zealand the “Implementing Soil Quality Indicators for Land – 500 Soils Project” is a government led programme of soil quality monitoring designed to meet “State of the Environment” monitoring requirements as required under the RMA. This project did not link soil quality indicators to a measure of the sustainability of land use at a site. Instead the data is used to make regional and land use based comparisons.

Five hundred and eleven (511) soils representing all NZ soil types and a range of land uses were characterised and analysed for 12 primary indicators. Analysis of the soil indicators suggested that a group of 7 indicators could adequately describe the soil quality (Sparling *et al.*, 2000). They are:

- Total C;
- Total N;
- Mineralisable N;

- Soil pH;
- Olsen P;
- Bulk density; and
- Macroporosity.

The group of indicators identified as useful in the 500 Soils Project can be further refined for use as soil quality indicators for forests. The use of pH as an indicator is of limited value for forest soils where pH is typically low. Tree crops as managed in New Zealand are typically well adjusted to low pH soils and can grow successfully in a wide range of soil pH. A change in pH however, may indicate a detrimental change in soil quality.

The measurement of Olsen P as a measure of soil available P is well understood to be poorly related to plant available P in forest soils. In addition, while the measurement of Olsen P may adequately describe the supply of P for an agricultural crop of short duration, the longer rotation length of a forest crop becomes more dependent on other forms of P, in particular organically bound P.

Thus, removing P as a measure, relevant indicators for forest soils may be:

- Total C;
- Total N;
- Mineralisable N;
- Bulk density; and
- Macroporosity.

3.3 New Zealand LTSP2

Research into the links between soil quality and sustainability of NZ forests is presently underway. The NZ LTSP2 has been established with the stated aim to identify those site characteristics that control the productive capacity of forests. The NZ LTSP2 is a network of research plots set-up at 35 sites representing the geo-climatic zones under forest cover in NZ. Monitoring at the sites includes 11 soil chemical and 6 soil physical parameters. Results from the LTSP2 programme will be used in the development of a soil quality index of sustainability for NZ forest soils. At present the study is in its first rotation and information is limited. Initial results suggest that soil physical characteristics influencing drainage (air capacity and sand fraction) as well as the soil carbon to nitrogen ratio and base saturation levels may be indicators of sustainability (Watt *et al.*, 2005).

A media release dated 8 April 2008 indicates that the NZ LTSP2 is at the stage where results are being used to propose a set of soil indicators for sustainability of NZ forests. While limited information has been disseminated to the forestry community at the time of the release of this report, it is understood that likely indicators proposed are:

- Total C;
- Total N:
- C:N ratio;
- Total P;
- A horizon depth; and
- Porosity.

Scion forest scientists aim to set up a service for analysis and interpretation of soil quality measures of sustainability. The proposed program and associated costs are as yet undisclosed, however it is anticipated that the outputs will be strongly related to the results of the LTSP2 results, and likely similar to what is being suggested above. Data collected from a research based programme such as the LTSP2 provides a logical starting point for developing a soil quality index of sustainability that can be adapted for use in commercial forestry. It is acknowledged that the interpretation of soil quality measures of sustainability is, as yet, not well defined and so there may be some value in utilising Scion expertise for interpretation of results obtained in following the sampling and analysis program proposed here in the absence of available data.

Once the Scion programme has been revealed, it is of relevance to FOA to understand whether or not the LTSP2 programme may be used as a standalone system for understanding soil quality, or whether it requires augmentation with local data to be able to understand individual forests. Due to the large perceived requirements for data due to spatial heterogeneity and extent of forests, the value of a long-term forest condition monitoring system requires careful evaluation.

4.0 RECOMMENDATION OF SQI FOR NZ FOREST SOILS

If a forest condition monitoring system is to be implemented for NZ forest owners, It is recommended that it adopt measures related to processes easily influenced by soil management and whose selection is complementary to existing and emerging understanding of the impacts of management practice on soil quality and sustainability as studied worldwide, in particular the in LTSP programmes in operation in NZ and the US, which are both closely aligned and relevant to the NZ context. The adoption of a monitoring programme based on the USDA LTSP experiment (Powers *et al.*, 2005) would be a preferred approach. The original soil quality indicators used in the LTSP (soil porosity and organic matter) have been expanded. A set of four soil parameters, described as tier 1 indicators have been recommended for monitoring of forest soil condition. They are:

- Soil bulk density – the soil bulk density was selected to determine degree of compaction at a site. It is anticipated that changes to soil bulk density will only occur due to management induced effects. The effects of bulk density changes to sustainability vary with site factors such as soil PSD. However, over time significant changes in bulk density will impact the water holding and rooting capacity, impacting the sustainability of the forest operation;

- Soil total carbon – total carbon is understood to correspond to organic carbon for most NZ soils. Levels of carbonate bound carbon are negligible in most NZ soils. Soil C levels vary according to site factors and removal of organic matter. Removal of organic matter due to harvest and site preparation activities varies greatly according to practices adopted. Measuring total carbon enables degradation of organic matter pools to be detected. Degradation of organic matter pools are understood to have short and long term impacts on sustainability of the land use;

- Soil total nitrogen – the pool of total nitrogen in the soil is considered to be relatively stable. Changes in the total nitrogen indicate a change to the chemical status of the site which may indicate changes in the forest condition requiring investigation; and

- C:N ratio – the C:N ratio has established relationships to many ecosystem functions. The C:N ratio is related to the organic matter composition and nutrient cycling. The potential impact of the forest operation on C:N ratio is by interruption of the organic matter supply through removal of the forest floor, or activities that limit the biological productivity of the site including compaction, which affects the air and water dynamics of the soil, and organic matter removal. Alteration of the C:N ratio is likely to be attributable to a reduction in soil quality, corresponding to unsustainable practice in the forest operation.

The rationale for the selection of the soil parameters is given in Section 2. The nominated parameters are considered to meet, as far as practicable, the criteria for selection of soil quality indicators for a maximally broad selection of sites as described in Section 2.1. It is considered that the measurement of bulk density, total carbon, total nitrogen and the determination of C:N ratio as measures of soil quality will provide a substantial basis to determine the sustainability of a forest operation, and changes in these parameters would indicate a change in the forest condition over time.

Additional soil quality parameters could be adopted at specific sites. These are referred to as tier 2 indicators. The choice of tier 2 indicators is dependent on knowledge of the sampling site and these indicators are likely to be measured only in the event of a measured change in the tier 1 soil quality indicators, or an inability of those indicators to define the primary limitation to long-term sustainability. Tier 2 indicators should be assessed on a site by site basis. Where a site is understood to be limited by a specific deficiency or toxicity issue, appropriate tier 2 indicators should be included in the monitoring programme at that location. Tier 2 indicators include:

- Mineralisable nitrogen – mineralisable nitrogen is strongly related to microbial function and nutrient supply. Care should be taken to specify the method used in measurement of mineralisable nitrogen;

- Soil pH – soil pH may be recommended for incorporation into the monitoring programme for sites where inputs have the potential to affect soil pH significantly. Sites which may be considered for measurement of pH include those with a low buffering capacity for pH i.e. sandy sites or acidic soils. Soils whose initial pH is close to the extremes for growth of tree species may require pH to be monitored in combination with the tier 1 indicators;

- Total and available P – The value of total P as an indicator is dependent on the composition of the soil P. On soils with a large mineral P fraction the indicator may not be sensitive enough to detect changes due to forest management. Where the soil organic P fraction is small available P measures, particularly sequential Bray P extraction, is recommended over total P. Total P is recommended where soil P is dominated by the organically bound P fraction. On sites where P is known to be limiting and total carbon demonstrates a downward trend measurement of soil P is recommended. The P fraction measured should be selected in consideration of site factors.

- Base saturation or CEC – The measurement of base saturation or CEC may be required where soil organic matter is depleted as indicated by a downward trend in the total C of the soil. Both parameters will assist in determining remediative measures for a site believed to be degraded.

- Particle size distribution and macroporosity – In sites subject to compaction an understanding of the PSD of the soil will assist in predicting the effects of compaction on the sustainability of the forest operation. A reduction in macropore content of the soil occurs as a result of compaction. The macroporosity of the soil impacts the air exchange and water dynamics of the soil.

5.0 MONITORING PROGRAMME DESIGN

A sample monitoring programme designed for the purpose of monitoring forest condition to enable assessment of sustainability of forestry practices in New Zealand follows. The forest condition monitoring programme (FCMP) has been designed for measurement of soil quality indicators to demonstrate compliance with forest owner's obligations to maintain and improve forest condition. In consideration of a monitoring programme multiple end uses for the data have been considered to enable the programme to meet the requirements for a number of monitoring scales and purposes.

In reality, a monitoring programme chosen by FOA, or an individual forest owner, will be dictated by the finances available for such monitoring, the ability of the monitoring to augment the owner's knowledge of their specific forests, it's ability to complement existing monitoring requirements (e.g. carbon accounting, Forest Stewardship Council (FSC) certification requirements and RMA consent condition monitoring) and the requirement for the information to be translatable across regions and the country. The latter concepts are the principle reasons for incorporating a uniform testing regime across the industry, however it is important to carefully review the information collected in these areas to date, to assess whether such a system will truly add value to a forest owners understanding of their system.

The sample design of the FCMP chosen here incorporates sampling strategies used in research based monitoring programmes presently in use, specifically the New Zealand carbon monitoring system (CMS) (Davis et al 2004). The intention of this alignment is to enable multiple functions to be achieved from the FCMP, enhancing value, as described above. In the future, FCMP sampling may be able to be performed as an add-on to carbon accounting requirements, or vice versa. In addition, the FCMP, if designed properly may be used in the generation of state of the environment (RMA) or FSC certification data. The sampling design protocol for the FCMP is found in Appendix B.

The incorporation of methodology from the CMS is considered advantageous since it is an existing nationally used system, which has been extensively peer reviewed and is based on the Intergovernmental Panel for Climate Change (IPCC, 1996) default system.

The FCMP suggested is similar to the US LTSP and also is complementary to NZ LTSP. It is considered important that the programme can be related to research programmes to enable the incorporation of research results as they apply to forest condition monitoring. It is valuable, though, for FOA to consider that these LTSP programmes may better serve the industry as long-term monitoring, which may negate the need for an extensive FCMP, or have similar value, at a reduced cost to the FOA or interested parties.

For the FCMP, it is considered important that samples are taken at multiple depths. Depth is considered as a stability gradient for sustainability. Such that, changes occur rapidly, heterogeneously and transiently at the surface. Whereas, at depth in the mineral soil detectable changes are very slow and insensitive to transient effects. Thus, it is considered that a simple measure of topsoil may not adequately help to define long-term change.

5.1 Data Collation

It is recommended that a system for collation of data from the proposed FCMP be adopted following consultation with NZFOA members. There a number of potential options for operation of the FCMP, including:

- Individual company responsibility – data is collected and interpreted by the forest manager responsible for the site. The use of the data for the purpose of accreditation of product or similar is at the discretion of the forest owner/manager;

- NZFOA managed database – data collected is submitted to a database managed co-operatively within the NZFOA. The database can be used to develop interpretive tools for assessing sustainability;
- Independently managed database – data collected is submitted to an independent third party with the ability to interpret the data and can use the database to develop interpretive tools for assessing sustainability.

The choice of collation method would likely be determined by the relative importance of such data to an individual forest owner's operation as company IP. While we suggest that the information is of more value collectively here, and that its relevance to short-term rotation management may be limited, individual owners may have disparate views.

5.2 Factors Affecting the Successful Uptake of the FCMP

The FCMP differs from most of the systems currently in place worldwide in that it is not a research project. For the FCMP to be adopted for use by New Zealand forest owners and managers the FCMP must be clearly related to an outcome, being a measure of sustainability of forest management practice. This differs from existing programmes in that they are designed to establish relationships between site management and soil quality. In addition, the skill sets and objectives of the personnel responsible for the organisation and execution of the programme shift from that of research scientists to that of practitioners.

In development of a sampling design and plot layout consideration must be given to the time and to the degree of technical difficulty involved in set-up, sampling and interpretation. In consideration of the sampling programme a balance must be struck between obtaining a statistically valid dataset with a scientifically defensible design and a sufficiently simple methodology that it can be performed accurately by workers of varying skill levels.

It is expected that a cost will be associated with any monitoring programme, however the cost must be reasonable to forest owners to ensure that the programme is successfully adopted. Some of the costs associated with the FCMP will include:

- Personnel costs – identifying and sampling plots. Training and familiarisation;
- Field equipment – it is likely that additional equipment will need to be purchased for conducting field sampling. The equipment may vary widely in price depending on degree of automation required and availability; and
- Analysis costs – soil analyses will require specialised measurement. Rough costs of analyses are provided in Table 4.

Laboratories selected for comparison are:

- Hill Laboratories (Hills) – The largest commercial laboratory in New Zealand. Offers a wide range of testing.
- Veritec – Scion's (formerly Forest Research) commercial laboratory. Specialises in forest soils. Included since many forest managers get foliage testing performed through Veritec.
- Analytical Research Laboratory (ARL) – Wholly owned by Ravensdown and offering soil testing and fertiliser recommendations.

The use of the above laboratories for comparison does not indicate endorsement. It should be noted that there are many other suitable laboratories in NZ. The intention is to examine the price range and availability of a representative cross-section of potential analysis providers.

Table 4: Laboratory Comparison

	Hill Laboratories	**Veritec**	**ARL**
Analysis Costs			
Total carbon	$41 Package including Min N.	$22	$20
Total nitrogen			
C:N ratio			$25
Bulk density	NA[3]	$8	NA[2]
Tier 2 indicators			
Mineralisable N	Above	NA[2]	$15
pH	$44 as part of fertility test[4]	$7	$40 as part of fertility test[4]
Total P	$25	$25	$23
Available P	Olsen P as part of fertility test[4]	$ 33 Bray, $25 Olsen	Olsen P as part of fertility test[4]
CEC/base saturation	Part of fertility test[4]	By arrangement	Part of fertility test[4]
PSD/macroporosity	NA	$38 PSD	Sub contracted
Other Information			
Accreditation	IANZ	-	IANZ
Interlab proficiency[1]	ASPAC, WEPAL	ASPAC	ASPAC
Sample bags supplied	Yes	By arrangement	Yes

1. Laboratories participate in interlaboratory proficiency programs as a part of a quality assurance program.
2. Laboratory presently does not offer test but has indicated that they would set-up a service as required.
3. An equivalent analysis, moisture content, costs $25 at Hills and this value has been used as a maximum value for estimate purposes.
4. Test is part of extended test typically including pH, Olsen P, exchangeable cations (Ca, Mg, K), CEC and base saturation.

It is likely that Scion, as CRI for the forest industry will be offering an interpretation service for a suite of soil quality measures that are similar to those proposed in this report. There will likely be an associated cost for this service. The NZFOA should be satisfied that interpretation is based on research that has undergone rigorous peer-review.

5.3 Likely Data Requirements and Cost for an FCMP

Cost relative to the value of the information retrieved from an FCMP is likely to be the most important factor in deciding whether or not to pursue such a long-term programme. Here we briefly describe the likely costs on a per plot basis, coupled with the likely requirement for plot intensity, to obtain a very rough, preliminary cost estimate for the data collection and interpretation for an FCMP. In addition we have provided several alternatives worth investigating, should the value of FCMP-type information be recognised, but the cost unable to be justified.

5.3.1 Estimate of Per Plot Costs

Based on the analysis costs outlined in Table 4 the analysis cost per plot, sampled as described in Section 9, is likely to be in the range of $384-$856 for the tier 1 indicators. Assuming a half to full day cost for staff or contractors to gather the samples, it is likely that a per plot cost is likely to be in the range of $2,000 - $3,000. This includes costs for travel, sampling, shipping of samples to a laboratory for analysis, and a small charge for equipment hire, or usage depreciation. It is also expected, though, that this value would drop substantially if a team was dedicated to systematically measuring sites over the course of a season.

5.3.2 Intensity of Plots Required for an FCMP and Associated Costs

As outlined in Appendix A "Criteria for Site Selection" a relatively conservative requirement for plot intensity is 120 plots to cover the extent of plantation forests in New Zealand. This is largely dependent on the degree of variation in management practices and the number of replicates required.

Based the number of plots and the costs outlined in Section 5.3.1 the predicted costs of establishing a plot network vary from $280,000 to $460,000. This excludes establishment and maintenance of a data management system since the costs associated with data management would be dependent on the system chosen by the NZFOA. During an approximately 30 year rotation the monitoring procedure will be repeated a total of three times as outlined in Appendix A.

The cost to individual companies would be a proportion of the above most likely reflecting the proportion of total New Zealand forested land owned by the company.

5.3.3 Alternatives to Implementing an FCMP

Briefly, there are several potential alternatives to implementing an FCMP that could be explored:

- Engaging Landcare Research and Scion to collate existing research data for forested environments, and examining the potential use of this information prior to developing a standalone FCMP.
- Using the LTSP 2 Trial data, and relating it to nearby conditions, through a proposed Scion programme.
- Examining the potential to 'piggyback' additional tests onto the national carbon monitoring programme.
- Deciding that such a long-term programme may not provide information that is materially useful to the operation of NZ plantation forests and is not required, as current reporting for multiple international, national and forest owner level sustainability objectives (Montreal Process, CMS, FSC, RMA) are worthy surrogates and have the potential to detect long-term change.

We note that there are many trials that have occurred in the past 30+ years that have monitored several or all of the parameters that have been suggested above, however these trials or their information do not reside in a common database from which comparisons can be drawn. It may be of value to the FOA to commission a collation and update of this information, which would cost materially less than a full scale FCMP programme, yet may yield information that is highly valuable prior to the further measurement of these key criteria.

6.0 DATA INTERPRETATION AND SUMMARY

Assuming that an FCMP is undertaken, the selection of soil quality indicators of forest condition assumes a relationship between the indictor and sustainability of the practice. A number of approaches to quantifying sustainability from soil quality have been used in the literature. Frequently an index of soil quality is developed from additive or multiplicative models where soil quality indicator values are rated according to established ranges. The rated values are combined with factors determined from sufficiency curves to give an index of sustainability. The specificity of soil quality monitoring is a potential problem with the use of a soil quality index (Kelting *et al.*, 1999). To successfully predict sustainability from a soil quality index model the amount of data required to accurately model sustainable forest condition is substantial. The amount of information needed is prohibitive to the adoption of this type of model. Insufficient data may lead to an index which is poorly related to sustainability.

The present state of knowledge of the relationship between forest condition as described by soil quality, and sustainability is in the early stages of development. There is no doubt that management practices affect the soil quality of a site. However, a review of the literature indicates that the scale and direction of these effects is highly variable and frequently strongly influenced by non-management induced factors such as soil type, climatic, geologic and temporal effects.

In the absence of a definitive model to describe the forest condition, the US (and subsequently Canada) and Australia have adopted approaches whereby any detectable change is considered to correspond to degradation of soil condition. Due to the high degree of heterogeneity in forest soils the level at which variance corresponds to a statistically significant difference is high. According to the US LTSP research, in the case of most indicators a change of >15 % is necessary to detect a change in measured soil indicators with confidence (Powers *et al.*, 2005). In Australia a change of between 15 and 30 % depending on the indicator, corresponds to a detectable change in the measured soil indicator. In both programmes a detectable change will trigger a management response. The management response triggered may be as simple as comparing the change in the measured indicator with the net productivity of the forest stand.

It is recommended that an FCMP adopt a similar approach in the absence of well defined relationships to sustainability of land use in New Zealand forests. A change in any indicator of >15 % should trigger a monitoring response. It should be noted that the detection of a change in an indicator does not at present directly correlate to a change in the forest condition.

The sampling design is structured to include information from different phases of the crop rotation. Soil processes are likely to be affected by the differing phases of tree growth and management and so management responses should be based on trends in forest condition data, and not on single results.

In order to detect a change in forest condition a baseline condition needs to be defined. Due to extensive monitoring of New Zealand forests historically, sufficient data may exist to infer a baseline condition for a monitoring site. Where existing information is not available the baseline must be taken as the condition at the first sampling period.

The direction of change of an indicator should not be taken to infer degradation or improvement of forest condition. Any change should be monitored since even a positive change in an indicator may cause limitation of other forest and ecosystem functions. For instance, oversupply of N and corresponding toxicity following canopy closure is increasingly identified as an issue in northern hemisphere forests (Moffat and Kennedy, 2002). And further, soil compaction as determined by increases in bulk density was determined to have a positive effect on tree growth in a sandy soil and a negative effect on tree growth on finer textured soil (Powers *et al.*, 2005).

Armacher *et al.* (2007) noted that there is a need to start exploring any statistical associations between soil quality and measures of soil health to infer relationships that will enable the development of a soil quality index. As the results of trials worldwide aimed at quantifying sustainability in forests progress it is anticipated that the interpretation of soil quality data will become more refined. The FCMP recommends a conservative approach in the interim as described above.

A management response should be triggered by:

- A change in one direction of a measured indicator which exceeds 15 % difference from the initially measured value for 3 consecutive sampling periods i.e. the trend extends beyond one rotation;
- A change in one direction of a measured indicator which exceeds 15 % for the first and 30 % for the second sampling periods after the initially measured value; or
- A substantial change from the initially measured value which cannot be explained by sampling error. In this case the expertise of the forest manager should be used to determine what corresponds to a substantial increase. It is likely that changes will be noted in more than one indicator.

The initial action taken will be to assess likely causes of changes. In this case tier 2 indicators should be used to characterise the site more fully. The tier 2 indicators selected should be based on the forest manager's knowledge of the site management history and an understanding of the local conditions (climate, landform, soil type).

6.1 Interpretation of Soil Quality and Sustainability

For the FCMP to be of use to forest managers it must have a measurable relationship to sustainability. To enable operational decisions to be made based on soil quality they must be able to be related to beneficial, neutral or detrimental impacts on sustainability at a site. The ability of the FCMP to quantify the soil quality at a site will determine its value as an indicator of sustainability.

At the present the understanding of direct relationships between soil quality and sustainability of a land use are limited. This is discussed in more detail in Section 10. Approaches used for assessing the impact of soil quality on sustainability in NZ include:

- Differences in soil quality indicators across different land uses, where a baseline of soil quality is represented by an undeveloped site. Sites are partitioned by properties such as soil type and parent material, climate, topography and biota. Groups of sites with similar properties can be directly compared. Benchmark sites must be established for each combination of site properties to enable a baseline for soil quality to be defined. The 500 Soils project compares soils in this way; and
- Changes in soil quality indicators at the same site over time. This approach allows variation due to factors other than soil quality to be integrated into a site specific assessment of sustainability. Benchmark sites must be established across the range of site properties to account for spatial variation in the impact of soil quality indicators on sustainability. The LTSP2 programme can be used in this way.

With both approaches data is collected which can be used to describe the soil quality of a site. However the relationship of the soil quality to the sustainability of the land use is not implicit. For the FCMP to be successful there needs to be clear guidance as to the application of soil quality data to the management decision process for forest managers.

6.2 Future Development of a Soil Quality Index

There is a growing database of soil quality information for NZ soils from systems such as the 500 Soil project and the LTSP2 programme. While insufficient information from the LTSP2 has been published to independently develop a soil quality model of sustainability for NZ forests, the data may be available upon application where funding comes from “public good” sources such as FRST.

The CMS project, which is funded by the Ministry for the Environment (MfE) has an extensive database of total C and bulk density data across a wide range of sites and land uses. If total N data was obtained for these sites there may be potential for development of a soil quality index incorporating the indicators proposed for the FCMP. The use of this data would enable the comparison of forested sites with undeveloped sites of similar characteristics, representing a benchmark of soil quality corresponding to sustainable land use.

Further investigation is required in this area.

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APPENDICES

Appendix A
Proposed FCMP Protocol

CRITERIA FOR SITE SELECTION

It is well demonstrated in the literature that in addition to management induced changes, variances in soil indicators of forest condition are strongly influenced by climate and by soil type or geological setting. These factors are well understood for New Zealand forests and are described by LTSP and Soil 500 programmes. In selection of sites for FCMP, as many climatic zones and soil types should be represented as possible.

There are a number of factors to be considered in the selection of sites for ongoing forest condition monitoring, including:

- Segregation of edaphic and environmental zones;
- Number and spacing of sites;
- Method for determining sites (random, regular grid); and
- Data to be used in determination of site location (GIS, Landsat).

It is recommended that criteria for establishment of a plot network should be decided in consultation with stakeholders to ensure that both, local and industry knowledge informs the selection criteria, and to gain support for the FCMP through stakeholder involvement in decision making. In addition a biometrician should be consulted.

To ensure that a representative cross section of sites is obtained the site selection will most likely be based on three variables. They are:

- Soil type – The New Zealand Soil Classification recognises 15 soil groups (Hewitt, 1992). Of these, over 99 % of plantation forests occur on 8 of the groups (Watt *et al.*, 2005);
- Climatic Zone – the local climate is known to have a significant impact on the productivity of forests, and therefore should be accounted for in the selection of sites; and
- Management – measurement of soil quality must take into account the impact of management practices and therefore, for each soil/climate zone the range of different management practices should be represented.

Due to the inter-related nature of climate and soil development it is likely that not all soil groups will occur in each climatic zone. The Land Environments of New Zealand (LENZ) project (Landcare Research) applies a classification incorporating soils, landform and climate information. The Level 1 classification describes 20 zones which account for the environmental variation inherent in the forest ecosystem. Any LENZ level 1 zone containing more than 1000 ha of plantation forest should be included as a replicate in selection of sites.

In each zone differing management practices should be treated separately. While the selection of practices will have some relationship to the environmental considerations of the site, it is likely that differences in practices between forest owners will occur. For the purposes of this report, a maximum of six different practices in each LENZ zone have been considered. This gives a potential requirement for 120 sites. In addition, replicates of each site may be required to produce a statistically valid data set which could increase the number of sites by threefold or more.

The site selection criteria will be used to define an area in which a sampling plot can be located. The site should be large enough to allow the selection of a plot with a buffer zone on each side of not less than three rows of trees between the site and any areas subject to unusual disturbance such as:

- Roadways, permanent tracks;
- Waterways, including annual high water level; and
- Areas of other human induced disturbance which may affect the management of the site (eg meteorological station, excavation).

The final decision on plot location should be the responsibility of the forest manager, who will have the best local knowledge of the area to be sampled.

SAMPLING SCHEDULE

Typically, sampling frequency for research based monitoring programmes is a 5-10 year return period (US LTSP, CMS, SOE). Powers et al (2005) note however, that results obtained from a 5 year return period are influenced by short term perturbations. These effects may be related to settling of soil following site prep activities and tree establishment effects.

Since the purpose of this programme is monitoring longer term trends in forest condition, it is recommended that sampling frequency is related to phases of forest growth and management. Sampling will be carried out as follows:

- Tree establishment – the site will be sampled at 3-4 years post plant. The site should be sampled prior to fertilisation to ensure effects due to application of fertilisation and, where relevant, site disturbance do not influence the sampling results.

- Pre commercial thin or at 13-15 years – the plot will be sampled at this time to record the forest condition after canopy closure. The site should be sampled prior to thinning (where this occurs) to exclude effects of recent site disturbance.

- Pre-harvest – the plot will be sampled at this time to record the forest condition at the end of the crop rotation, prior to substantial disturbance.

The objective of the proposed sampling frequency is to obtain soil quality data corresponding to the different soil processes occurring during the distinct phases of forest growth. The importance of soil quality monitoring during the tree establishment phase of the crop rotation is because this phase most closely represents the soil quality if management inputs were ceased and the site were returned to its indigenous vegetative cover as described in Section 2.2. In addition, soil quality is likely to be strongly influenced by the growth of the crop through root exploration and litter fall, whereas soil quality measured prior to canopy closure is a more sensitive measure of the soils ability to recover from significant disturbance. This may lead to earlier detection of detrimental change in the soil quality before it influences the forest condition and long term sustainability.

The measurement of soil indicators after canopy closure is likely to correspond to significant influence of the crop on soil quality. This phase is considered to be indicative of soil quality as under continued forest cover.

For a number of soil quality indicators, particularly soil physical indicators, the recovery of the indicator following disturbance is slow and may only be measurable after a number of years. The measurement of soil quality indicators pre-harvest enables the recovery of indicators to be assessed for a longer time period.

ESTABLISHMENT OF MONITORING PLOTS

Locating the Plot

Following the selection of plot location, the site must be established for sampling and identified to enable the site to be relocated for subsequent sample periods. The centre of the plot should be referenced using map co-ordinates and GPS readings. Details of the location should be recorded on a site description sheet as given in Figure 1 (Appendix A). To assist with relocating the site a metal peg may be driven into the soil at depth, which can be found using a metal detector.

Where possible, it is recommended that a nearby permanent feature such as a trig, rock outcrop, river bend, etc is included in the plot location notes. Include the description, distance and bearing (note whether the bearing is from the plot to the feature or from the feature to the plot).

Plot Layout

A plot of dimensions 20 m square is to be demarked at the location. The plot is further divided into four quadrants which are individually sampled. The correct layout of the plot is critical to the validity of the results and so care should be taken in laying out the plot markers. Allow at least two hours to locate and set up the plot before sampling.

At the centre of the plot two 20m tapes are to be laid at right angles, 10m either side of the centre. The tapes should be laid along the contour and down the profile of the slope respectively. Each of the corresponding quadrants is to be sampled. A diagram showing the plot layout is given as Figure 1 (Appendix B).

Describing the Plot

A unique plot identifier (ID) should be given to each plot. The ID is to include information about the location/zone and will be given a number which is not to be repeated at any other site in the network.

Data regarding the site to be recorded on a standardised site description sheet may be obtained prior to the site visit. Information regarding geomorphic position should be confirmed at the site.

During the site visit observations regarding the site cover should be recorded including stocking rate of trees, areas of bare ground, presence of slash, litter, rutting or other signs of disturbance.

Information that may be recorded prior to the site trip describing the edaphic and environmental conditions at the sites should be obtained. Additional information to be recorded or confirmed at the site includes:

- **Landscape** – this is the major land unit of the area e.g. hill country, incised plateau, river plain etc;
- **Landform** – this is the land unit within the landscape e.g. ridge, spur, terrace etc;
- **Landform element** – this describes the position on the landform where necessary e.g. mid-slope, hummock etc;
- **Slope** – record the angle of the bulk of the plot using a clinometer. Record the plot aspect using a compass where the plot is located on a slope;

- **Percent cover bare soil** – this is a visual assessment and includes any area where the organic or mineral soil is exposed i.e. not covered by vegetation, slash, etc; and
- **Percent and type of soil compaction** – this is a visual assessment and includes any area with obvious signs of compaction such as vehicle tracks (wheel tracks only), high use areas (turning, parking etc) and any other compactions with a description of the mode of compaction.

The first four parameters listed above need only be recorded at initial plot establishment. The last two parameters describe a dynamic state and should be described at each sampling period. Where possible photographs should be taken as these offer a simple visual comparison between sampling periods.

SAMPLING PROTOCOL

In sampling the soil of the plot it is separated into organic soil – consisting of fine woody debris (FWD), litter (L) and humus (FH) – and mineral soil. Different sampling procedures are adopted for each organic and mineral soil samples. When referring to samples the plot identifier and sample date should be included.

Sampling of Organic Soil

Due to the difficulty in differentiating the divisions of the organic soil, the FWD, L and FH horizons are combined as a single sample. In each of the sample plot quadrants, two samples are taken at random points within the quadrant and composited to give a total of four forest floor samples for each plot.

To sample, a 0.1 m^2 (31.6 cm x 31.6 cm) quadrat is pegged on the site with aluminium tent pegs or similar. Before removing the sample, the depth of the organic layer at the mid point of each of the four sides should be recorded on the site description sheet. Secateurs or a sharp knife should be used to cut around the perimeter of the quadrat to separate material that extends beyond the boundary.

The material comprising the organic soil is collected carefully from within the quadrat. Attention should be paid to the organic-mineral soil boundary and ensuring no mineral soil is incorporated into the sample. Organic material larger than 2.5cm diameter and stones should be discarded a far as practicable. Material from the two quadrats in each quadrant are combined and removed to a labelled plastic bag showing collection date, identifying the plot, the sampler and the sample identification number (ID). The sample ID should indicate that the sample is organic by use of the identifier O. The quadrant number which corresponds to a number between 1 and 4 as described on the plot layout sheet is included in the sample ID. Sample IDs are therefore O1, O2, O3 and O4. Material should be kept cool and sent to the laboratory for processing within 3 days of collection.

Sampling of Mineral Soil

To ensure that results can be compared with data obtained for research based programmes, in particular the NZ LTSP2 and US LTSP, and are able to be related back to the CMS programme, mineral soil should be collected to a depth of 0.3m in 0.1m increments such that samples are collected for 0-100mm, 100-200mm and 200-300mm depths. Where samples for each of these depths are not able to be collected the reason should be noted on the site description sheet.

Sampling for soil bulk density is done using metal rings of known volume. Depth of the rings should be 100mm and the diameter of the rings should be recorded on the site description worksheet. After removal of the organic soil from the quadrat and removal of the frame, soil bulk density samples should be taken at one quadrat location for each quadrant giving a total of 12 bulk density samples.

The bulk density rings are hammered into the soil, level with the surface. The rings are then carefully excavated from the location with as little disturbance to the underlying soil as possible – subsequent depths 100-200mm and 200-300mm are then sampled and excavated carefully in the same manner. All soil from within the ring should be carefully transferred to a labelled plastic bag. The label should include the collection date, plot identifier, sampler and sample ID. The sample ID should indicate that the sample is for bulk density by use of the identifier BD. The quadrant number which corresponds to a number between 1 and 4 as described on the plot layout sheet is included in the sample ID. A letter corresponding to the depth increment, as well as the depth increment is included. Sample IDs are therefore:

BD1A (0-100)	BD1B (100-200)	BD1C (200-300)
BD2A (0-100)	BD2B (100-200)	BD2C (200-300)
BD3A (0-100)	BD3B (100-200)	BD3C (200-300)
BD4A (0-100)	BD4B (100-200)	BD4C (200-300)

Where bulk density is unable to be sampled using rings, e.g. in stony soils, the sample may be taken using the quadrat as the perimeter. Soil is then extracted using a spade and trowel in 100mm increments. Care should be taken to ensure the sides of the excavated pit are perpendicular to the soil surface.

Sampling for chemical analysis is performed using a soil corer of internal diameter not less than 25mm. The soil corer should be marked at 0.1m intervals. The organic soil should be removed prior to core samples being taken. Where a corer cannot be used, e.g. stony soils, samples may be taken from excavated pits. Four samples are to be taken along the contour of the plot on either side of the quadrat. Samples are taken at 0.25, 0.50, 0.75 and 1.0m either side of the quadrat.

The collected cores for each quadrant should be combined to give one sample for each depth for each quadrant. A total of 16 cores are combined to give one sample for each depth, in each quadrant. A total of 12 soil samples are obtained. Samples should be stored in labelled plastic bags and kept cool. The label should include the collection date, plot identifier, sampler and sample ID. The sample ID should indicate that the sample is for soil analysis by use of the identifier S. The quadrant number which corresponds to a number between 1 and 4 as described on the plot layout sheet is included in the sample ID. A letter corresponding to the depth increment, as well as the depth increment is included. Sample IDs are therefore:

S1A (0-100)	S1B (100-200)	S1C (200-300)
S2A (0-100)	S2B (100-200)	S2C (200-300)
S3A (0-100)	S3B (100-200)	S3C (200-300)
S4A (0-100)	S4B (100-200)	S4C (200-300)

Samples should be sent to the laboratory for processing within 3 days of collection.

Transfer of Samples to Laboratory for Analysis

Samples should be transported to the laboratory in chilly bins. Where tier 2 analyses are to be performed, particularly mineralisable N, the samples should be refrigerated and sent to the lab for analysis within 48 hours of sampling. Samples for analysis should be accompanied by a standardised chain-of-custody form. Samples are to be analysed at a laboratory using standard methods. The laboratory chosen should be able to demonstrate that quality assurance procedures are followed.

Appendix B
Figures

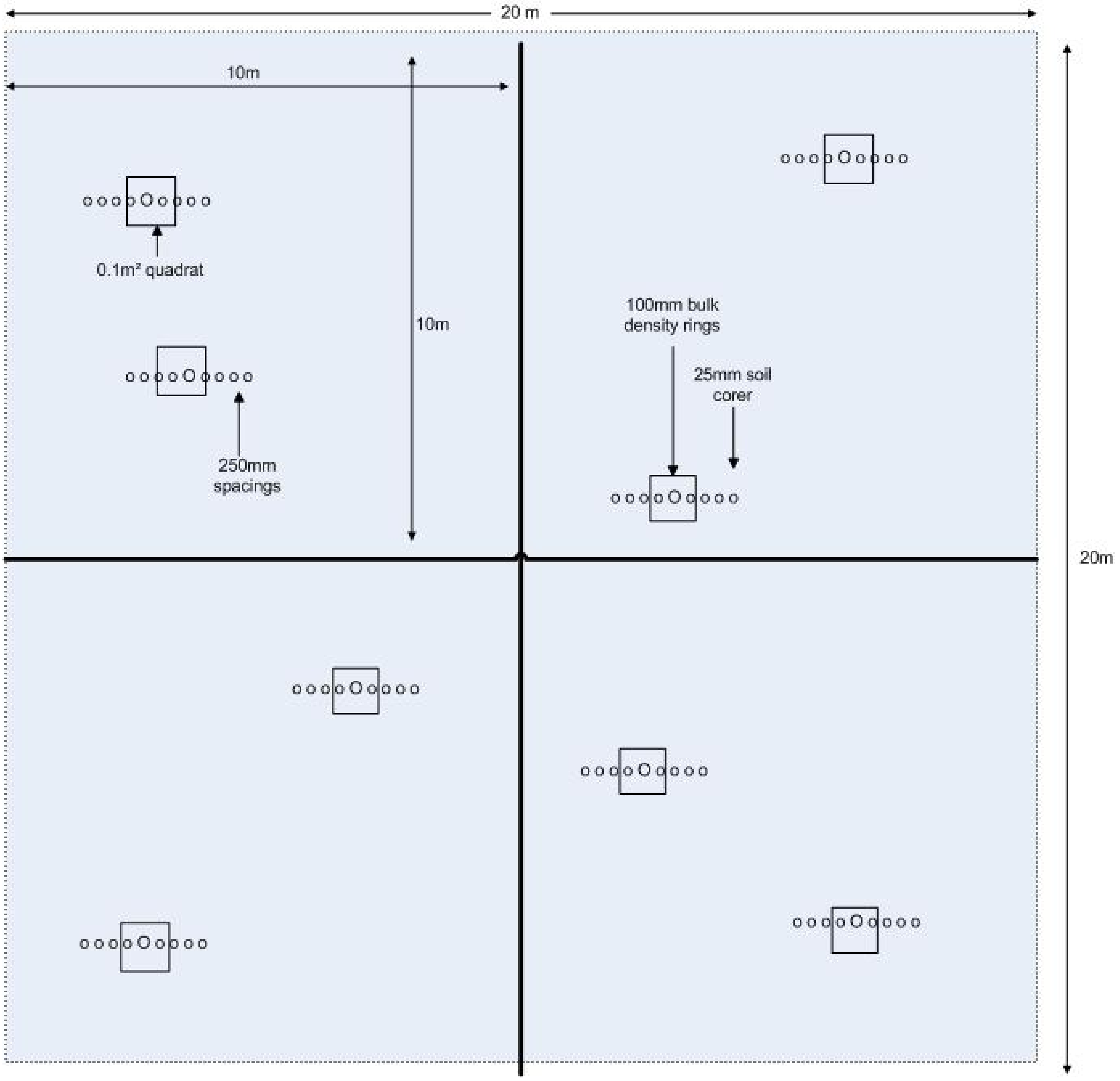

Figure 1: Layout of Forest Condition Monitoring Plot