Impacts of forest harvesting on the performance of soil-landscape modelling in a radiata pine forest, northern New Zealand

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ABSTRACT

New Zealand's forestry industry requires new information on the spatial distribution of certain target soil properties and locally significant soil classes in order to implement sustainable and site-specific forest management practices. Soil-landscape modelling has been identified as a potentially useful tool for collecting this information. However, its performance in plantation forest environments – where the impacts of forest management on soils can be considerable – has not yet been comprehensively evaluated. As a step towards such an evaluation, this study was undertaken to determine and assess the impacts of hauler-based, clear-fell, forest harvesting on the performance of soil-landscape modelling as a tool for the spatial prediction of soil classes and target soil properties in a radiata pine forest. The research was conducted within southern Mahurangi Forest, an exotic, *Pinus radiata*-dominated plantation forest, situated on the Northland Peninsula, North Island, New Zealand.

Three major sub-studies were conducted. In the first, the impacts of forest harvesting on the performance of the qualitative soil-landscape modelling approach to the spatial prediction of soil drainage classes (identified as locally significant) were determined. In the second, the impacts of forest harvesting on the predictive relationships used by quantitative soil-landscape modelling and class-based (including semi-quantitative soil-landscape modelling) approaches to the spatial prediction of target soil properties were determined. Harvesting impacts on the magnitude and variance of the target soil properties (topsoil pH, available Mg, available P, available K, macroporosity, and total C) were also examined. In the third sub-study, the impacts of forest harvesting on the performance of seven techniques representing the class-based, quantitative soil-landscape modelling, and geostatistical approaches to the spatial prediction of target soil properties were determined and compared. Four class-based techniques (labelled 1-4 and based on soil drainage classes, landscape units, and soil-landscape units), two quantitative soil-landscape modelling techniques (multi-linear regression and regression kriging), and one geostatistical technique (ordinary kriging) were investigated.

All sub-studies were undertaken primarily within two separate, but essentially adjacent 5-ha sampling plots. One plot was under first rotation mature *Pinus radiata* trees, i.e. the pre-harvested plot; the other plot had been harvested and was under second rotation, two-year-old trees, i.e. the post-harvested plot. Each plot consisted of 208 sample points on a 16.7-m regular grid pattern. The pre-harvested plot was effectively the control plot and hauler-based, clear-fell, forest harvesting was the treatment applied to the post-harvested plot.

The predictive models were developed (and predictive relationships investigated) using only 146 of the data points so that the remaining 62 points could be used to validate the predictions. A separate qualitative soil-landscape model was developed for each plot in general accordance with the land systems approach. The performances of the techniques for predicting the target soil properties were evaluated and compared using several statistical measures including mean error, root-mean-square error, goodness-of-prediction, mean rank, and standard deviation of rank. The predictive relationships between the target properties and the soil drainage classes, landscape units, and soil-landscape units were described using a least-squares-means analysis of variance whereas the relationships between the target properties and the terrain attributes (derived from a 5-m digital elevation model) were described using the squared-multiple-correlation statistic.

The soils of southern Mahurangi Forest differ predominantly in terms of soil drainage condition. A modified version of the New Zealand soil drainage classification was defined to partition better the local variation in soil profile hydromorphology (e.g. the existing imperfectly drained class was subdivided into two new classes). The modified drainage classes were amalgamated into two broad drainage classes (Wet soils and Dry soils) to improve the practicality of the qualitative soil-landscape models. The relationships between the broad drainage classes and the landscape units were found to be fractionally weaker in the post-harvest plot than in the pre-harvested. However, the weaker relationships are probably attributable to the generally drier nature of the landscape in the post-harvested plot and are not likely to be due to forest harvesting. The qualitative soil-landscape models were applied to predict the spatial distribution of the broad drainage classes within their respective plots. The performance of the models was good, with both registering correct predictions at >80% of the validation points.

Therefore, forest harvesting had no detrimental impact on the predictive performance of qualitative soil-landscape modelling.

Forest harvesting was found to have had a significant impact on the magnitude of all target properties. The means of some target properties (topsoil pH, available Mg, and macroporosity) were significantly decreased whereas the means of other target properties (available P, available K, and total C) were significantly increased after harvesting. The variance of some target properties was also found to have been significantly affected by forest harvesting. The variance of topsoil pH and available Mg was significantly decreased whereas the variance of total C was significantly increased after harvesting. Moreover, forest harvesting altered and weakened the relationships between most target properties and the modified soil drainage classes and landscape units. Also, the correlations between most target properties and the terrain attributes were weaker after forest harvesting. However, the relationships between most target properties and the broad drainage classes and soil-landscape units were not altered or weakened by harvesting.

Most techniques for the spatial prediction of target soil properties gave less biased and slightly less accurate predictions of most target soil properties after forest harvesting. Furthermore, most prediction techniques offered less of an improvement in accuracy over the sample mean after harvesting for most target properties, meaning that most techniques became relatively less useful after harvesting. Considering all target soil properties together, the relative performance of some prediction techniques (regression kriging and ordinary kriging) generally became poorer whereas the relative performance of other techniques (class-based 2, class-based 3, and class-based 4) generally improved after harvesting. On balance, the relative performances of the class-based 1 and multi-linear regression techniques remained the same. Ordinary kriging (the geostatistical technique) is the best predictor of target soil properties in the pre-harvested areas of southern Mahurangi Forest whereas the class-based 2 technique (a semi-quantitative soil-landscape model) is the best within the post-harvested areas. Furthermore, the class-based 2 technique has the potential to offer a more practical and cost-effective alternative to ordinary kriging throughout the forest. The other techniques (e.g. the quantitative soil-landscape models) either failed to perform well after harvesting or were likely to be less cost-effective, or both.

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The Unity of One

Once
There was only one soil
In all our worlds

For you
A Martock brown earth
In a cider orchard
On the Isle of Avalon

No need for maps
No doubts
No arguments

You were the one
Who often asked
Why did we have to
Find another
And another?

David van der Linden

CHAPTER ONE

General introduction

1.1 Background

The movement of New Zealand's forestry industry towards sustainable and site-specific forest management has created new and specific demands for forest soil information. Quantitative, precise, and detailed information on the magnitude and variability of certain target soil properties (i.e. key soil indicators of sustainable forestry), in addition to accurate information regarding the spatial distribution of locally significant soil classes (e.g. drainage classes), is essential for assessing and monitoring forest site quality and for implementing site-specific forest management programmes (Payn and Thwaites, 1998; Turner *et al.*, 1999; Payn *et al.*, 1999, 2000; Fox, 2000; Shaw and Carter, 2002). There is also a commercial desire for this soil information to be collected in a cost-effective manner and presented in easily accessible, flexible formats (Payn and Thwaites, 1998).

Most existing soil information relating to New Zealand's forest estates is inadequate, being generally qualitative, sparse, and mapped at scales too coarse for the comprehensive assessment of forest site quality and the implementation of site-specific forest management (Payn and Thwaites, 1998; Payn *et al.*, 1999, 2000). Therefore, the required soil class and target soil property information must be collected before sustainable and site-specific forest management can be achieved (Payn *et al.*, 1999).

Although it is now widely recognised that conventional soil survey is unable to adequately provide the required detailed soil information (McKenzie and Austin, 1993; Moore *et al.*, 1993; Payn and Thwaites, 1998; Thwaites and Slater, 2000), the most suitable approach to collecting soil spatial information in plantation forest environments has not yet been clearly established. However, some studies have made progress towards identifying methodologies suitable for acquiring, analysing, organising, and presenting forest soil and tree-growth data in New Zealand (e.g. Jones, 1998; Hill, 1999; Hill *et al.*, 2000; Payn *et al.*, 1999, 2000).

The identified methodologies involved the use of soil-landscape modelling, geographic information system (GIS), and pedometric (e.g. geostatistical) tools. Soil-landscape modelling, in particular, has been highlighted as a potentially useful tool for the collection of soil spatial information in plantation forest environments (Jones, 1998; Payn and Thwaites, 1998; Hill, 1999; McKenzie and Ryan, 1999; Thwaites and Slater, 2000). When used in association with pedometrics and spatial information technology (e.g. GIS), soil-landscape modelling has the potential to provide the required soil class or target soil property information in appropriate formats (e.g. McLeod *et al.*, 1995; Rahman *et al.*, 1997; Payn and Thwaites, 1998; Thwaites and Slater, 2000; Schmidt, 2002). Furthermore, the soil-landscape modelling approach may be cost effective because it predicts soil distribution from readily available and relatively cheap ancillary (explanatory) landscape information (Hewitt, 1993), such as digital elevation data. Pedometric tools for mapping soil properties such as geostatistical interpolation (usually via kriging) techniques have generally been shown to be effective in intensively sampled areas or where there is relatively strong spatial dependence (e.g. Kravchenko, 2003). However, the potentially large number of samples required to achieve an adequate level of prediction accuracy across large forest estates may make this approach excessively costly (McKenzie and Austin, 1993; Kravchenko, 2003).

The soil-landscape modelling approach to soil spatial prediction has generally been found to perform well in agricultural and range-land environments (e.g. McLeod *et al.*, 1995; Odeh *et al.*, 1995; Rijkse and Trangmar, 1995; Bishop and McBratney, 2001) and its potential usefulness within plantation forest environments has been recognised (Jones, 1998; Hill, 1999; McKenzie and Ryan, 1999; Hill *et al.*, 2000; Thwaites and Slater, 2000). However, the suitability of soil-landscape modelling to plantation forest environments has not yet been comprehensively evaluated. Forest land-management activities such as clear-fell harvesting can cause considerable soil disturbance (Simard *et al.*, 2001; Palmer *et al.*, 2004) and have been shown to significantly alter the magnitude of soil properties in both New Zealand (e.g. Parfitt *et al.*, 2002) and elsewhere (e.g. Simard *et al.*, 2001). Therefore, the soil-landscape relationships used by soil-landscape models to predict soil spatial distribution patterns may be altered or weakened by forest harvesting (Block *et al.*, 2002) which, in turn, may reduce the predictive performance of soil-landscape models. However, the impacts of forest harvesting on soil-landscape relationships and the predictive performance of soil-landscape modelling had not been investigated. Nor had the impacts of forest harvesting on the performance of other approaches to soil spatial prediction (e.g. class-based or geostatistical prediction techniques) been determined. Gaining an understanding of the impacts of forest harvesting on the predictive performance of soil-landscape models is therefore a crucial step towards the comprehensive evaluation of their suitability to plantation forest environments.

1.2 Aim

The overall aim of this research was to determine and assess the impacts of hauler-based, clear-fell, forest harvesting on the performance of soil-landscape modelling as a tool for the spatial prediction of soil classes and target soil properties in a radiata pine forest. The research was conducted within southern Mahurangi Forest, an exotic, *Pinus radiata*-dominated plantation forest, situated on the Northland Peninsula, North Island, New Zealand.

1.3 Objectives

The specific objectives of the research were as follows.

1. To determine the impacts of hauler-based, clear-fell, forest harvesting on (a) the relationships between locally significant soil classes and landscape units, and (b) the performance of the qualitative soil-landscape modelling approach to the spatial prediction of locally significant soil classes.

2. To determine the impacts of hauler-based, clear-fell, forest harvesting on (a) the magnitude and variance of the target soil properties, and (b) the relationships between the target soil properties and the soil classes, landscape units, soil-landscape units, and terrain attributes.

3. To determine and compare the impacts of hauler-based, clear-fell, forest harvesting on the performance of seven techniques representing the class-based, quantitative soil-landscape modelling, and geostatistical approaches to the spatial prediction of target soil properties.

1.4 Thesis structure and chapter outline

Following this general introduction, the thesis comprises six chapters including a literature review (Chapter 2), a description of the study site (Chapter 3), three chapters of the main findings (Chapters 4, 5, and 6), and a chapter where these are synthesised and over-arching conclusions are made (Chapter 7). Four appendices are also included. Rather than listing them at the end of the thesis, the references cited within a chapter are given at the end of that chapter. This is because the chapters are presented generally in a stand-alone format to facilitate their publication ultimately as journal articles. Because chapters 4–6 share some common methodology, cross-referencing to previous chapters is used to avoid repetition.

Chapter 2 is a literature review that examines soil-landscape modelling as a tool for the spatial prediction of soils in plantation forest environments. It also introduces the concepts of soil spatial variability, considers the failings of conventional soil survey, discusses the current requirements of forest managers for soil information, and describes the role of pedometrics and spatial information technology in soil-landscape modelling and soil mapping.

Chapter 3 describes the location, natural environment, and management history of the study area (southern Mahurangi Forest). Also, the existing information relating to the soils of the forest is reviewed and previously mapped soil series are described and redefined.

In Chapter 4, the spatial distribution of soil drainage classes – which I demonstrate to be the most appropriate classes for partitioning soil variation within the study area – is established and predicted (mapped) using qualitative soil-landscape models. The impacts of forest harvesting on the relationships between the soil drainage classes and the landscape units are identified. The results of model validation are given and the impacts of forest harvesting on the predictive performance of the qualitative soil-landscape models are determined.

Chapter 5 examines the impacts of forest harvesting on the magnitude and variance of the target soil properties. Also, the impacts of forest harvesting on the relationships between the target soil properties and the soil drainage classes, landscape units, soil-landscape units, and terrain attributes are determined. The implications of the results for forest management are discussed and justification for the proposed modification of the New Zealand soil drainage classification is given.

In Chapter 6, the impacts of forest harvesting on the performance of seven techniques representing the class-based, quantitative soil-landscape modelling, and geostatistical approaches to the spatial prediction of target soil properties are determined and compared. The best performing techniques before and after harvesting are identified and the suitabilities of the various techniques to plantation forest environments are discussed in relation to the impacts of harvesting on their performance.

Chapter 7 provides a summary and synthesis of the results given in Chapters 4, 5, and 6 in addition to listing the main conclusions of this research.

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CHAPTER TWO

Soil-landscape modelling: a tool for soil spatial prediction in plantation forests

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2.1 Introduction

Because soil properties vary spatially, some parts of the landscape need to be managed differently from others to maximise economic productivity while ensuring the sustainability of land resources (Phillips, 1993a). However, the very nature of soil spatial variability leads to difficulties in making precise statements regarding the spatial distribution of soil classes or properties (McBratney, 1992). The challenge for the pedologist is to rationalise soil spatial variability in order to accurately and efficiently identify areas of soils that may be managed either similarly or differently and to effectively communicate these variations to land managers.

Soil survey, coupled with general purpose soil classification systems represents the conventional approach to the rationalisation of soil spatial variability (Di and Kemp, 1989) and to the collection and communication of soil information. However, the recent literature suggests that the nature of soil information required by land managers, such as forestry companies, has changed. Moreover, it is now widely recognised that conventional soil survey cannot adequately meet these new soil information requirements (Hammer *et al.*, 1991; Moore *et al.*, 1993a).

An extensive body of research promotes soil-landscape modelling, in association with spatial information technology and pedometrics, as a new approach to the collection, analysis, and presentation of soil spatial information with the aim of meeting the new soil information requirements of land managers. However, little research has been conducted into the applicability and suitability of soil-landscape modelling to exotic plantation forestry environments.

This review will first describe briefly the origins and nature of soil spatial variability before considering the ways of conceptualising soil spatial variability and the conventional approaches to dealing with it (i.e. soil survey and soil classification). Arguments proposing the need for a new approach to the collection and communication of soil information will then be outlined. Geographic information systems (GIS), terrain analysis, and pedometrics – which play key roles in supporting soil-landscape modelling and in the analysis and provision of soil information – are then discussed in turn. Soil-landscape modelling, in its qualitative and quantitative forms, is presented as a new approach to soil mapping. Methods for mapping of soils using spatial interpolation techniques are also examined.

2.2 Origins of soil spatial variability

It has long been recognised that soils and their constituent properties differ from place to place in the landscape. In other words, soils (and soil properties) are spatially variable (Phillips, 1993a).

2.2.1 Pedogenesis and the factors of soil formation

The idea of a factorial approach to pedogenic theory was first explored in Russia during the late nineteenth century by V.V. Dokuchaev and his students and contemporaries. Similar ideas were proposed by E.W. Hilgard at around the same tie in the USA (Yaalon, 1989) but were neglected essentially for political and other reasons (Amundson and Yaalon, 1995; Simonson, 1997). The 'formational-factorial' theory eventually became more widely known and it was endorsed and further advanced by H. Jenny among others (Johnson and Hole, 1994). In the seminal text *Factors of Soil Formation,* Jenny (1941) presented the formational-factorial approach in the form of the 'state factor' model which has provided a conceptual framework for pedological research since its publication (Wilding, 1994).

2.2.1.1 The state factor model

It was Jenny's aim to develop quantitative relationships between the soil-forming factors and soil properties in order to describe how the latter varied with the former. The state factor model considered the soil to be a dynamic open system that is part of a much broader environmental system. Five potentially independent environmental factors defining the state of the soil system, and therefore controlling its formation, were identified: climate, organisms, topography, parent material, and time. The state factor model holds that:

$$S \text{ or } s = f(cl, o, r, p, t, \ldots)$$

where S represents the soil; s represents any soil property; and cl, o, r, p, t, and . . . represent climate, organisms, topography, parent material, time, and additional local site factors, respectively (Jenny, 1941).

The state factor approach can be summarised as follows. Climate, organisms, topography, and parent material interact over time (Bunting, 1965) to dictate the nature of the pedogenic processes which operate to form the soil at any given point in the landscape. The pedogenic processes in turn influence the nature of the soil properties. A difference in at least one of the soil forming factors through space – from one point in the landscape to another – can lead to the operation of a different set of the pedogenic processes and, in turn, to spatial differences (variability) in soils and soil properties (Huggett, 1982; Donald *et al.,* 1993). Thus, variation in the soil forming factors through space is one of the main causes of soil spatial variability. Furthermore, the state factor model provides a conceptual framework in which the main drivers of soil spatial variability can be understood and explained. In deed, the formational-factorial paradigm has provided the theoretical underpinning for soil survey and mapping in the USA (Johnson and Hole, 1994) and also provides the theoretical foundation for soil-landscape modelling.

There are a number of limitations to the state factor model. First, the above equation has never been, and possibly cannot be, solved (Birkeland, 1999). This may be because most of the factors are difficult to quantify and rarely act independently (Bunting, 1965). Difficulty in quantification arises largely from an inability to collect the required data (Schelling, 1970). As the soil forming factors change through time, the formation of most soils is likely to have been influenced by more than one set of soil forming factors. This phenomenon, known as polygenesis, may also preclude solving the equation (Birkeland, 1999). Also, the state factor model does not recognise that soil profile morphology may evolve to the point that it can influence pedogenesis independently of external environmental conditions (factors) (Johnson and Hole 1994). The implication of this omission is that soil spatial variation can occur without necessarily being driven by spatial differences in the state factors. Furthermore, the state factor model does not recognise that pedogenic processes may act degenerately as well as constructively (Bunting, 1965) nor does it say much about pedogenic processes (Wilding, 1994). For example, the importance of biomechanical processes is not explicitly recognised by the 'organisms' factor which tends to be associated more with biochemical processes (Johnson and Hole, 1994).

In an attempt to mitigate some of these limitations, alternative pedogenic models have been proposed, including materials-energy flux models (e.g. Simonson, 1959; Runge, 1973) and, more recently, the *i*-level hierarchical model (Hoosebeek and Bryant, 1992). However, Yaalon (1975) concluded that the theoretical basis of the state factor model had, at that time, not been successfully challenged. Birkeland (1999) stated that despite its limitations, the state factor model allows for valid qualitative and occasionally quantitative predictions to be made (including by Jenny, 1980). Phillips (1989) suggested that the state factor model is more useful for understanding soil variability than the alternatives. Also, modifications and enhancements of the original state factor model have been made. For example, Johnson and Watson-Stegner (1987) proposed an evolution model of pedogenesis that takes account of soil degeneration (regressive pedogenesis) as well as development (progressive pedogenesis). Johnson *et al.* (1990) refined this model further by emphasising changing rates of pedogenesis and also the role of upbuilding processes. This refined model is known as the dynamic-rate model of pedogenesis.

2.2.2 Land management effects

As biological organisms, humans are a part of the organic factor of soil formation (Amundson and Jenny, 1991). However, humans, together with their technology, have the ability to significantly alter the soil like no other organism. Humans can influence the soil directly via mechanical disturbance or indirectly via modification of the some of the other soil-forming factors. Land management activities such as additions of fertilisers or organic material (e.g. slash), mechanical mixing, disturbance, or compaction; drainage and irrigation, and changes to vegetation cover all act to modify the soil and overprint the effects of the natural soil forming factors (Bidwell and Hole, 1964). Moreover, the natural soil-landscape relationships may be overprinted, altered, and obscured by such activities over time (a history of land management). Therefore, the relationships between soils, parent materials, and topography may be difficult to establish and the variability and distribution of soil properties (particularly fertility-related properties) may be significantly influenced by various land management practices (Daniels and Hammer, 1992; Dobermann *et al.*, 1995).

2.2.3 Deterministic chaos

It is possible that deterministic chaos is an additional source of soil spatial variability. It refers to the apparently random, complex patterns that result from nonlinear deterministic systems (Phillips, 1998). It cannot be attributed to scale effects or other controls. It should not be confused with stochastic complexity that results from the complex spatial variability of environmental factors and occurs at such a large scale that it is impracticable to model or describe. Deterministic chaos is characterised by sensitive dependence on initial conditions and increasing divergence with time. This means that even the smallest difference in any of the soil forming factors could result in significant and continually increasing differences in soil properties. The implication is that even when all the soil forming factors are apparently constant over an area, the soils could be extremely variable (Phillips, 1993a; Phillips, 1993b). Soil variability that was previously thought of as random noise may be, in part, accounted for by deterministic chaos, suggesting that a larger proportion of soil variability is systematic. That is, soil formation is responsible for some of the apparently random variability (Phillips, 1993b; Phillips *et al.*, 1996).

2.3 The nature of soil spatial variability

Soils not only vary laterally (horizontally) through space but they also vary vertically. Furthermore, soil spatial variability can change through time (Barrett and Schaetzl, 1993). This study is primarily concerned with the lateral component of soil spatial variability.

Soil spatial variability may be greater in some landscapes than in others depending on the nature of the processes that formed a given landscape (Daneils and Hammer, 1992). The variability of soil properties are complex and vary with scale because soil-landscape processes operate over various spatial scales and at different rates and may change through time (polygenesis) (Huggett, 1982; Gessler *et al.*, 1995). Soil spatial variability may also be of a much larger magnitude and occurring over larger scales (several metres or less) than was previously thought (Wilding, 1994). Anisotropy is a feature of virtually all soils, that is, the variability of soil properties differs with direction (Jenny, 1941).

Soil properties that are correlated may co-vary. That is, variation in one property may correspond to variation in another (Hole and Campbell, 1985). Such co-variation may be reflected in equal or opposite patterns of distribution. The co-variation among soil properties probably differs between spatial scales because different pedogenic processes operate over different spatial scales, some very large and others small (Dobermann *et al.*, 1995).

The variation in soil properties is essentially continuous but may also be discrete to some extent. Some properties may be continuously variable whereas others may not (Hole and Campbell, 1985). Traditionally, soil variability was described using either of two theoretical models, the discrete model (variation partitioned by map units) or the continuous model (variation described by a mathematical surface) (Burrough, 1993). Today, continuous (fuzzy) classification applies aspects of both models to offer a potentially more realistic approach to describing soil spatial distribution (Verheyen *et al.*, 2001).

Two main types or components of soil variability have been recognised: (1) systematic, which is a result of variation in the soil forming factors; and (2) random, which has no known cause and is extremely complex (Wilding and Drees, 1983). The systematic component can be explained and to a certain extent is predictable.

The distinction between the two components is dependent on the scale at which observations are made. The larger the scale, the more the supposedly random variability is found to have structure (Burrough, 1983). Most variability is systemic and predictable. However, the confidence with which predictions can be made is often low. Furthermore, at very large scales our understanding of landscape processes is often lacking and so predictions can not be made with a high level of confidence (Daniels and Hammer, 1992).

It is widely reported that soil variability tends to increase with decreasing scale (Figure 2.1) (Beckett and Webster, 1971; Wilding and Drees, 1983; Grigal *et al.*, 1991). However, it is also commonly reported that there is considerable large-scale variability in soil properties (Burrough, 1983; McBratney, 1992). In contrast, Gibson *et al.* (1983) found that variability decreased with decreasing scale. As a consequence of the nature of soil variability, different soil properties tend to vary differently (Gibson *et al.*, 1983).

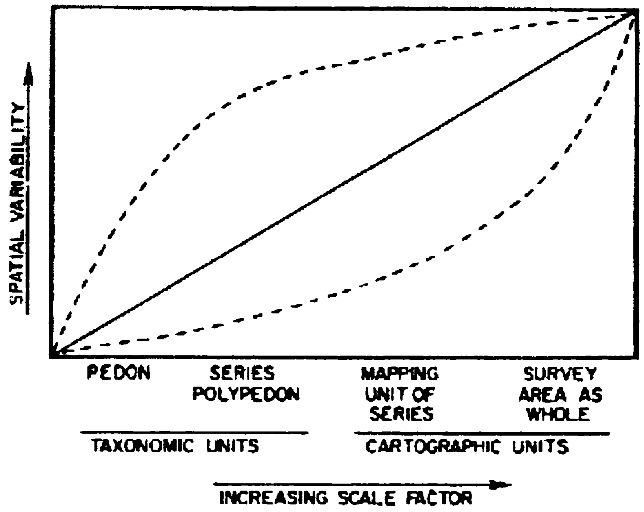

Figure 2.1. A schematic graph illustrating the increase in variability with increasing scale (From Wilding and Drees, 1983, p. 103).

Nested structures in the variation of soil properties are the result of the combined influence of different sources of spatial variability operating over distinct spatial scales. The greater the influence of a particular source, the greater the importance of the corresponding spatial structure (Dobermann *et al.*, 1995). The study by Dobermann *et al.* (1995) identified three distinct structures in the variability of soil chemical properties using experimental variograms: long-range linear (sill has a slightly positive slope), short-range spherical (lag distance), and a nugget value. The long-range linear structure was indicative of a down-slope trend possibly related to the down-slope movement of cations.

Dobermann *et al.* (1995) found that soil chemical properties are generally highly variable. Properties such as pH were found to be the least variable with CV values around 3% whereas available P was the most variable property with CV values ranging from 148-164%. They also found the nugget variance to be high for most topsoil properties. Enoki *et al.* (1996) showed that soil depth was more variable than fine earth content with CVs of 105% and 36%, respectively.

2.4 Conceptualising soil spatial variability and the conventional approach to dealing with it

2.4.1 Spatial concepts of soil

2.4.1.1 The soil-landscape paradigm

The soil-landscape paradigm is based on Jenny's state factor model and serves as the general model of soil geography and is the guiding model/philosophy of soil survey and soil-landscape modelling (Hudson, 1992; Hoosbeek, 1994; McSweeney *et al.*, 1994). Landscape units can be identified as areas of natural terrain which are the product of the interaction between the soil forming factors (Hudson, 1992). The genetic relationships between soils and landscape unit can be used to predict soil spatial distribution. The key concepts of the soil-landscape paradigm are summarised by Hudson (1992) as follows: (1) there is one main soil class within each landscape unit; (2) the greater the difference between two adjacent landscape units, the more sharply defined their boundary will be; (3) the more similar the landscape units, the more similar the soils; (4) the spatial relationships of two adjacent landscape units are predictable; (5) and the establishment of soil-landscape relationships may allow for the prediction of soil classes from landscape features (Hudson, 1992).

The validity of the soil-landscape paradigm means that soil classes can be delineated reasonably accurately from the landscape. However, it may have the weakness of being inefficient as it relies on the tacit knowledge and experience of pedologists. Most of the information that the soil-landscape paradigm gathers is presented as a report together with a soil map (Hudson, 1992). The application of the soil-landscape paradigm to studies of soil distribution and mapping often involves the catena concept.

2.4.1.2 The catena concept

Topography is both a landscape characteristic and a key factor of soil formation. This notion is embodied in the catena concept (Petersen *et al.*, 1995). A catena is a topographically-related sequence of soils repeated throughout the landscape (Conacher and Dalrymple, 1977). This concept supports the idea that there is a unique relationship between soils and their position in the landscape (Hall and Olson, 1991) which allows for the spatial prediction of soils (Dalal-Clayton, 1988). It also integrates the study of geomorphic processes and water movement with pedogenic processes (Hall and Olson, 1991). According to Conacher and Dalrymple (1977), the catena concept constitutes the basis and framework for much research in pedology and has considerably influenced soil survey. The investigation of catenary variations in soil properties assists with the mapping and classification of soils, which in turn provides important information for soil management (Agbenin and Tiessen, 1995). Two types of catena are recognised: (1) a simple catena, in which all soils are formed from the same parent material; and (2) a complex catena, where the soils have formed from two or more parent materials (Hall and Olson, 1991).

The nine-unit land surface model of Conacher and Dalrymple (1977) is a subdivision of a hypothetical, generalised slope profile and is founded on landform morphology coupled with current pedogenic and geomorphic processes (Figure 2.2). In accounting for down-slope fluxes of water, solutes, and sediments, the model integrates the individual slope components. The model combines Jenny's (1941) toposequence concept with the catena concept (Gerrard, 1990).

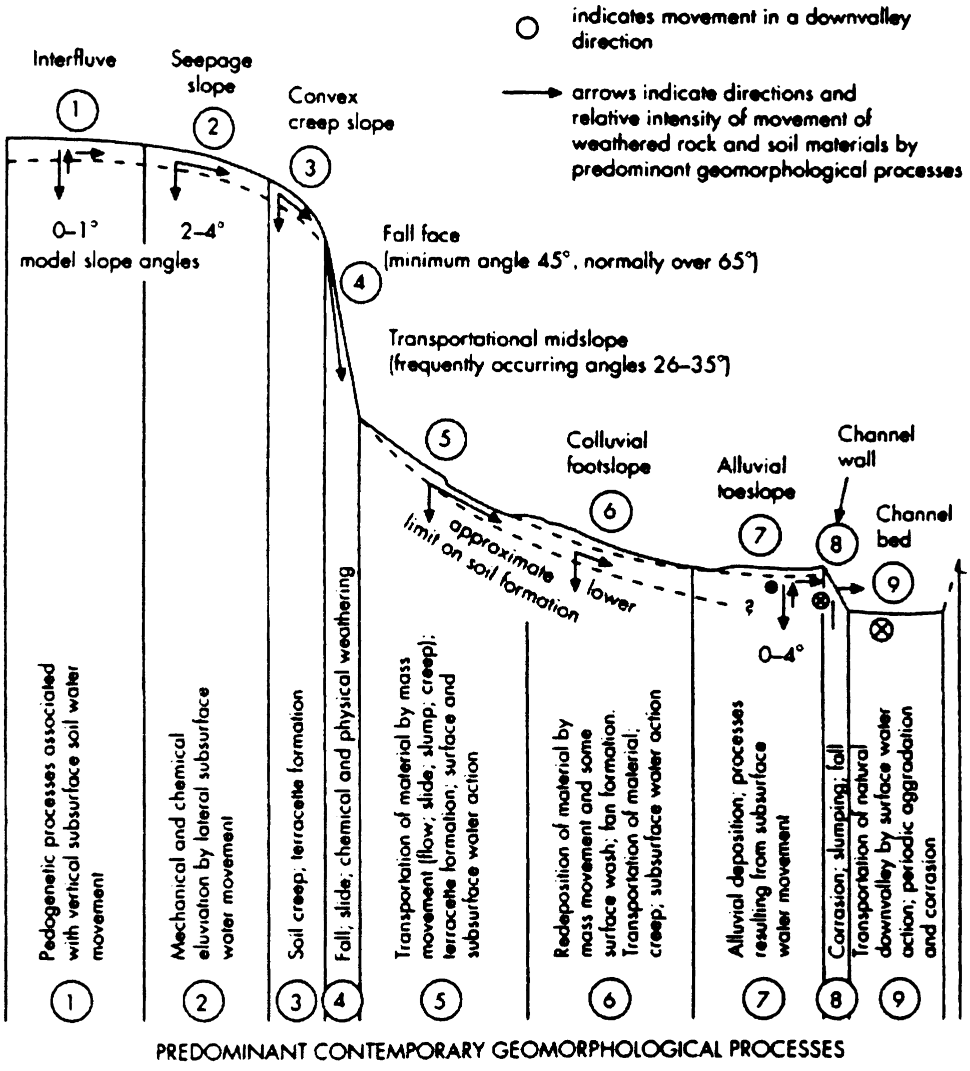

Figure 2.2. The conceptual nine-unit land surface model (From Gerrad, 2000, p. 168).

It has been clearly established that soil properties are related to landforms and landscape position (e.g. Gerrard, 1990; Hall and Olson, 1991; Moore *et al.*, 1993a). Furthermore, strong relationships between slope segments and soil variability have been demonstrated (Petersen *et al.*, 1995). Lee *et al.* (1988) stated that the terrain attributes of elevation, slope, and aspect all influence soil variability and so should be considered in studies of soil distribution. Moreover, Walker *et al.* (1968b) found strong relationships between soil properties and the elevation and slope components of topography. Also, Moore *et al.* (1993a; 1993b) found that the terrain attributes that characterise drainage networks have a spatial distribution that is indicative of the spatial distribution of soil properties. This is probably the result of the relationship between terrain attributes and hydrological and erosion processes (Moore *et al.*, 1993a). Hall and Olson (1991) argued that the influence of topography on hydrological and microclimatological processes is critically important to pedogenesis. Daniels and Hammer (1992) stated that the main factor driving pedogenesis is geomorphologically and stratigraphically controlled soil hydrology.

Water movement is thought to be a very important factor influencing geomorphic and pedogenic processes (Hall and Olsen, 1991). Hall and Olsen (1991) attributed the relationships between soil properties and landscape position to differences in moisture movement. Moore *et al.* (1993b) suggested that there are clear relationships between landforms and hydrological processes, and that the pedogenesis of a soil catena is influenced by the nature of water movement through a landscape. Donald *et al.* (1993) found that soil property variability was a function of soil moisture regime and landscape morphology. Variation in the storage of water and its movement over and through the soil is influenced by the spatial distribution of terrain attributes and, in turn, is related to the spatial distribution of soil properties (Donald *et al.*, 1993; Irvin *et al.*, 1997). For example, Moore *et al.* (1993b) found that aspect and plan curvatures are strongly related to soil moisture content. However, soil water storage and movement on hill-slopes are very complex because they are influenced by a host of different factors (Gerrard, 1990). Therefore, the resulting pattern of soil property distribution may be complex also.

Gerrard (1990) suggested that our understanding of soil-geomorphic relationships and the resulting patterns of soil distribution could be greater and more detailed if it were not for some methodological and conceptual impediments. Several impediments to developing soil-geomorphic relationships were identified by Gerrard (1990). These included the difficulty of defining geomorphic units in complex landscapes consisting of continuous (rather than discrete) surfaces, the constraints and ineffectiveness of regression analysis, the potential inappropriateness of applying the catena concept, and the occasional lack of relationships between present topography and soil properties (Gerrard, 1990).

The concepts of the catena and the land-systems approach to soil-landscape modelling (section 2.7.3.1) are founded on the assumption that relationships between soil properties and slope components only exist if the relationships between hill-slope and pedogenic processes have reached a steady state (Gerrard, 1990). Furthermore, these concepts assume that geomorphic and pedogenic processes are integrated within an individual slope and that soil-geomorphic relationships recur within a landscape (Gerrard, 1990). Gerrard (1990) refuted the assumption "that many slopes are integrated along their entire length" (p. 225), arguing that it will not always hold true. He stated that the lack of integration of slope components brings into question the utility of the catena concept for studying soil-geomorphic relationships. Gerrard (1990) also described several examples of landscapes in which recurring patterns of soil-geomorphic relationships were not present.

The catena concept may be an inappropriate model of soil distribution in humid temperate areas because soil-topography relationships are likely to have been complicated by climatic and vegetative fluctuations, human action, common superficial deposits (i.e. upbuilding), and parent material complexity (Gerrard, 1990). Moreover, the lack of integration of slope components and soils over large areas considerably reduces the applicability of the catena concept. To account for complexity in landscapes resulting from complex landscape evolution, concepts permitting a temporal analysis of catena are needed (Vreeken, 1984). Several workers have attempted the integration of temporal analysis into the catena concept. The K-cycle concept of Butler (1982) is an example. However, Gerrard (1990) suggested that the soil-landscape chronogram approach of Vreeken (1984) is the most comprehensive. More than the two geomorphic factors employed by the catena concept, slope steepness and geomorphic position, need to be investigated when assessing soil-geomorphic relationships (Gerrard, 1990).

2.4.2 Conventional soil survey and soil classification

Soil spatial variability means that exact statements about the distribution of soil properties and classes are difficult to make (McBratney, 1992). Soil survey has been defined as "a field investigation of soils in a given area" (Rogowski and Wolf, 1994, p. 163) and as the "systematic examination and mapping of soils in the field" (Allaby and Allaby, 1990, p. 345).

2.4.2.1 Soil survey: collection of soil information

Conventional soil survey applies the discrete model of variability in which the landscape is subdivided into discrete, supposedly internally homogenous units (delineations), the boundaries of which represent abrupt soil discontinuities (Hole and Campbell, 1985). There are two main survey methods, grid survey and free survey. With grid survey, soil descriptions are made in a regular pattern whereas the soil surveyor locates soil description according to his/her judgement in a free survey (Bridges, 1982).

Soil surveys have the purpose of determining the spatial distribution of soil classes across the landscape (Butler, 1980; Rogowski and Wolf, 1994; Jungerius, 1985). From a practical point of view, the role of soil survey is to map areas that can be managed differently from others (Beckett and Webster, 1971). Soil surveys vary in accuracy, complexity, and detail (Rogowski and Wolf, 1994). The main aim of soil survey is to provide soil information to land managers to allow them to manage the use of land resources (Maclean *et al.*, 1993). However, Wilding *et al.* (1994) stated that it is not the intention of soil survey to deliver soil information at a site-specific level. The guiding paradigm of soil survey is known as the soil-landscape paradigm (Hudson, 1992).

Soil map units

Soil map units are typically characterised by soil classes (Hewitt, 1993). The soil property information relating to a soil map unit is provided by a modal or representative pedon (Burrough, 1991; McSweeney *et al.*, 1994; Rogowski and Wolf, 1994). However, this modal pedon provides little information about the within-map-unit variability (McSweeney *et al.*, 1994). A soil pedon is a three-dimensional soil profile slice and in New Zealand it is defined to be a soil individual (Hewitt, 1998). A group of like pedons is a polypedon. Soil-landscape units consist of an association of polypedons. These units generally correspond to soil map units (Zinck and Valenzuela, 1991).

Soil maps, and the map units they contain, represent tools for the prediction of soil characteristics at unvisited sites (Dent and Young, 1981). The aim of soil map units is to group together soils with similar properties important for management (Hammer *et al.*, 1991; Maclean *et al.*, 1993). Conventional soil map units generalise the patterns of soil spatial variability and thus may not have sufficient detail to facilitate the sustainable management of land resources (Maclean *et al.*, 1993).

The issue that has vexed soil scientists for decades is how to describe the continuous spatial variability of soils with precise, discrete units. The inability to resolve this issue means that within a soil map unit, few pedons meet all the criteria of the class to which they have been allocated (Burrough, 1991). That is, map units are not pure in taxonomic terms. The degree of taxonomic purity depends on factors such as survey intensity, map scale, taxonomic level, and the degree of soil spatial complexity (Di and Kemp, 1989). Beckett and Webster (1971) claimed that map units were, on average, only about 50% pure. Mokma (1987) found that of the map units investigated, 88% contained more than 15% inclusions. It is the potentially extreme variability of soil properties over short distance that falsifies the assumption that soil map units are homogenous (Rogowski, 1995). The modal soil pedon used to present the soil properties of a soil map unit does not account for this variation (Rogowski and Wolf, 1994).

2.4.2.2 Soil classification: communicating soil information

The soil information collected by conventional soil surveys is usually communicated in the form of soil maps and associated reports (Butler, 1980; Zhou *et al.*, 1991). The creation of soil maps involves the application of geographic and genetic relationships between soils and the landscape. However, these relationships are not often made explicit to the land manager (Bell *et al.*, 1992; Hudson, 1992). Instead, soil surveyors use mental models that relate soils to landscapes (Bell *et al.*, 1992). Bridges (1982) argued that both the soil map and survey report are critically important aspects of a soil survey because unless the collected information is effectively communicated, conducting the survey was a waste of effort.

General purpose soil classification is one means by which soil information can be communicated to land managers. Soil classification is applied to soil survey in two ways. Firstly, it may be used define polypedons in an attempt to map their distribution. Secondly, the distribution of landscape units is mapped and the soil classification is used to describe the soils they contain. The use of classification in the description of map units, based on landscape features, may be more appropriate than its use for delineating map units (Hewitt, 1993).

2.4.2.3 Problems and limitations of the conventional approach

It seems that the new soil information requirements of land managers are not adequately met by conventional soil survey. The potentially great short-range variation in soil properties means that conventional soil maps have considerable within-map-unit variability (Gessler *et al.*, 1995). Furthermore, most conventional soil maps do not communicate the variability of specific soil properties. Nor do they explicitly communicate soil-landscape relationships (Burrough, 1986; Moore *et al.*, 1993a; Indorante *et al.*, 1996). Thus, Moore *et al.* (1993a) concluded that conventional means of presenting and arranging soil information are not adequate for site-specific land resource management. Hammer *et al.* (1991) supported this by stating that more detailed soil information than is provided by conventional soil survey is needed.

Conventional soil survey is seen to have two main problems: soil boundaries may not be delineated accurately, and within-map-unit variability of soil properties is not adequately taken into account (Hall and Olson, 1991; Moore *et al.*, 1993a). Also, the scale of conventional soil maps precludes them from adequately reporting site specific soil variations (Indorante *et al.*, 1996). The inability of soil survey to effectively account for soil variability is a major impediment to the use of soil information (Wilding and Drees, 1983). Other disadvantages of conventional soil surveys include their high costs in both labour and time (Lynn and Basher, 1994a). McKenzie and Austin (1993) stated that quality of soil classification systems used for mapping is impairing the effectiveness of conventional soil survey.

Indorante *et al.* (1996) indicated that, in the face of the new requirements for soil spatial information, soil survey must change to meet these needs. More specifically, they suggested that soil survey products should be more quantitative, easily understood, and be able to incorporate new data. The within-map-unit variability of relevant soil properties needs to be quantified and communicated so that the soil information provided by soil surveys can be interpreted in the light of known confidence levels (Jarvis, 1982; Mclean *et al.,* 1993). The present interest in soil spatial information has precipitated the need for more quantitative assessment of soil-landscape relationships (McSweeney *et al.,* 1994). Field soil survey is still essential but a change in its role, and methodology, has been necessary (Thwaites, 1996). Techniques for producing large-scale soil maps at low cost are required (Moore *et al.,* 1993a). It is essential for soil surveys to quantify the magnitude, location, and causes of soil spatial variability but it is even more critical for soil surveys to effectively communicate this soil information in a flexible manner (Arnold and Wilding, 1991). The improved expression of soil variability may encourage the use of soil information (Beckett and Webster, 1971).

A pertinent example of the inadequacies of conventional soil map units was provided by Campbell (1973) who investigated the soil variation within two steepland soil mapping units in New Zealand. The concept of the steepland soil map unit was introduced to recognise the differences between steepland soils and those formed in other land systems. However, the complex nature of the patterns of soil distribution in steep country means that steepland soil map units contain considerable amounts of variability that cannot be expressed by a single modal profile. The identification and description of the catenary patterns of steepland soils would allow for much of the within-map-unit variability to be accounted for. These soil patterns can only be mapped at very large scales but can be communicated by describing the map units as steepland associations containing a soil series and several variants (Campbell, 1973).

2.5 Managing the spatial variability of forest soils: site-specific forest management

The concept of site-specific (precision) land management was originally introduced to improve the management of agricultural land (Auernhammer, 2001). More recently, the concept has been adopted by the forestry industry with a view to improving forest productivity whilst minimising the adverse environmental impacts of forest management activities (Turner *et al.*, 1999).

2.5.1 Soil information requirements

Soil spatial information is required for the sustainable management of land resources. Soil survey and the resulting soil maps have been, and continue to be, an essential tool for land management. Soil spatial information is also a critical ingredient to soil process models currently used for land management (Agbenin and Tiessen, 1995).

The demand for soil information is growing (Petersen *et al.,* 1995). Also, the nature of the required soil information is changing. Land managers now require precise information about the magnitude, spatial distribution, and spatial variability of specific soil properties rather than taxonomic classes (Bell *et al.,* 1992; Indorante *et al.,* 1996). Moreover, soil information must be accessible, in a variety of forms, and easy to understand (Indorante *et al.,* 1996). Quantitative information regarding the reliability of soil information is also required so that the confidence with which predictions can be made is known (Maclean *et al.,* 1993). It is likely that the advent and adoption of site-specific land management practices is the main driving force behind the new soil information requirements.

The calls for a new approach to the collection and provision of soil information have grown rapidly in the forestry industry, which has both urgent and particular soil information requirements. Soil information is of importance to forest management primarily because tree, establishment, growth, and harvesting inextricably linked to soil conditions (Turvey and Poutsma, 1980). The aspects of forest management in which soil information may be useful include drainage assessment, species selection, wind-throw hazard assessment, site index definition, nutrient requirements, erosion hazard assessment, trafficability assessment, and road making (Turvey and Poutsma, 1980; Jarvis, 1982).

Conventional soil survey and classification have been geared predominantly towards meeting the needs of agriculture and, as a consequence, the uniqueness of plantation forestry, – especially its long term nature – has largely been overlooked (Dent and Young, 1981). Significant forest productivity variations are observed within soil map units because soil series or general purpose classes tend to be too generalised and heterogeneous to be used for the evaluation of forest productivity (Gessler *et al.*, 1995; Jones, 1998).

Like agriculture, the forestry industry is moving towards the site-specific management of land resources. The associated increase in management intensity necessitates that important, large-scale soil differences are identified more precisely and that reliable information regarding the pattern of soil distribution (or target properties) be provided (Turvey and Poutsma, 1980).

2.6 Spatial data collection, analysis, and management tools

2.6.1 Geographic information systems

No single definition of Geographic Information Systems (GIS) exists in the literature. However, the consensus view is that GIS is a computer technology for the purposes of collecting, storing, organising, manipulating, analysing, and presenting spatially referenced data (Burrough, 1986; Avery and Berlin, 1992; Dangermond, 1992; Haines-Young *et al.*, 1993; Canter *et al.*, 1994; Petersen *et al.*, 1995).

In essence, GIS are tools for managing, analysing, and presenting spatial data. Hammer *et al.* (1991) stated that spatial analysis is the definitive capability of GIS whereas Luckman *et al.* (1990) and Watkins *et al.* (1996) saw spatial data management as its main strength. However, there is the view that the ultimate use of GIS is the facilitation of decision making based on analysis and interpretation of spatial data (Bonham-Carter, 1994).

The key characteristics which make GIS such a useful and versatile tool are that they can manage large quantities of spatial data, facilitate data updating, bring data from diverse sources together, and generate new information (Dangermond, 1992; Bonham-Carter, 1994; Hiscock *et al.*, 1995). Haines-Young *et al.* (1993) emphasised the flexibility of GIS, stating that GIS can process data in different ways to suit individual problems or situations.

Depending on the particular system being used, GIS have many different functions. Different authors have very different views as to the main and most important GIS functions. The functions that appear consistently in the literature are given here. Seven main types of GIS functions can be identified. These are: (1) data acquisition, (2) data organisation, (3) data and map manipulation, (4) spatial analysis, (5) spatial prediction, (6) data visualisation, and (7) product output (Luckman *et al.*, 1990; Hammer *et al.*, 1991; Mitchell, 1991; Valenzuela, 1991; Avery and Berlin, 1992; Dangermond, 1992; Fernandez and Rusinkiewicz, 1993; Bonham-Carter, 1994; Canter *et al.*, 1994; Petersen *et al.*, 1995; Kolm, 1996; Skidmore *et al.*, 1996).

2.6.1.1 Application of GIS to soil mapping

The above mentioned characteristics of GIS make them very useful tools for supporting the new soil-landscape modelling approach to soil survey and for improving soil survey as a whole.

The use of GIS in modern soil survey

GIS are already an important part of modern soil survey. In fact, one of the first applications of GIS was in soil survey where it was used for the automated production of soil maps (Burrough, 1991). Many soil survey agencies are using GIS as tools for providing soil information and this use is becoming the standard rather than the exception (Burrough, 1991). For example, the U.S. Department of Agriculture's Soil Conservation Service has assembled a spatial soil database for use with a GIS (Franchek and Biggam, 1992).

Soil survey involves the collection of large amounts of diverse data (often spatial). Therefore, GIS are ideally suited to storing, processing, analysing and displaying soil information (Zinck and Valenzuela, 1991). Furthermore, GIS have the ability to generate new (derived) soil information by reclassifying soil polygons, integrating soil polygons with other data planes, and calculating polygon attributes, and predicting soil property values (Burrough, 1991). Field sampling points can be accurately located by GIS which may allow for the development of more statistically robust sampling schemes (Gessler *et al.*, 1995). Burrough (1991) suggested that one of the main uses of GIS in soil survey is the creation of soil and special purpose suitability maps.

A new degree of quantification has been brought to soil survey by GIS. Its data storage and retrieval capabilities together with its exact representation of locations and elevation allows for the study of the spatial variation of soil properties to be more objective (Burrough, 1991). There is great potential for GIS to improve pedological research and soil survey precision and quality (Hammer *et al.*, 1991).

An example of the use of GIS for soil survey in the Guarapiche River Valley, Venezuela, was given by Weir (1991). A geomorphic soil map was digitised and attribute data from pedons were entered into the GIS, ILWIS. The polygon and attribute data were linked by the GIS. Three types of output products were produced, a digital elevation model (DEM), single property soil maps, and interpretive land use maps. The soil polygon map was draped over the DEM so that the spatial distribution of soil classes across the landscape could be visualised. The creation of single property and interpretive maps was done through the integration of the soil spatial and attribute databases (Weir, 1991).

The use of GIS in soil-landscape modelling

The new approach to soil survey, soil-landscape modelling, is being supported by the spatial analysis tools of GIS (Petersen *et al.*, 1995). Petersen *et al.* (1995) believed that GIS techniques may aid many facets of soil-landscape research. For example, the ability of GIS to collate a diverse range of data allows for the spatial analysis of landscapes to be rigorous and integrated. Petersen *et al.* (1995) went on to state that GIS "provides a flexible approach for querying and displaying soil information" (p. 87).

The potential exists for GIS to quantitatively describe and predict the spatial variability of soils and landforms more precisely (Hammer *et al.*, 1991; McSweeney *et al.*, 1994). The spatial analysis capabilities of GIS may also facilitate the integration of pedology and geomorphology by creating and linking databases of each for the purposes of studying soil-landscape relationships (Hammer *et al.*, 1991). The terrain analysis capabilities of GIS (incorporating a DEM) allow for the determination of landform attributes that may affect pedogenesis and thus soil spatial distribution (Odeh *et al.*, 1994). The spatial analysis techniques of GIS combined with mathematical algorithms can manipulate spatially related data to assess environmental processes that may be indicative of landscape processes (Moore *et al.*, 1993b). Bell *et al.* (1992) stated that GIS, together with statistical modelling and field sampling, form an integrated approach to the analysis of soil-landscapes.

Bell *et al.* (1992) provided an example of the use of GIS in soil-landscape modelling. Terrain attributes were derived from a DEM, geological maps, and topographic maps. Spatial analysis was used to derive secondary landscape attributes in order to define spatial relationships and thus predict the drainage class of the soil. The soil-landscape model predicted drainage classes that were compared along with a conventional soil map in which the polygons had been reclassified to reflect drainage class, to field observed drainage class. The soil-landscape model out performed the soil map, predicting 74% of the observation sites correctly compared to only 69% correctly predicted by the conventional soil map (Bell *et al.*, 1992).

GIS and the provision of soil information

The application of GIS to soil science research may be creating new soil spatial information demands on soil survey (Hammer *et al.*, 1991). Weir (1991) stated that the need for better quality soil data is being increased by GIS. In addition to this, Ventura and Savory (1993) stated that the way soil information is used is being changed by GIS. This change may, in part, be due to GIS making soil information more accessible. The flexibility of GIS is allowing for soil map users to be provided with the necessary soil information at the degree of detail that their land use dictates (Maclean *et al.*, 1993).

Indorante *et al.* (1995) suggested that GIS technology should replace published soil surveys because of their ability to flexibly create user and site specific soil maps. They see GIS as a permanent and dynamic soil database. In support of this, Indorante *et al.* (1996) stated that GIS should be the 'information heart' of a modern soil survey organisation. However, Maclean *et al.* (1993) argued that GIS is compounding the problem of soil spatial variability because the thematic soil maps they produce give an unrealistic impression of homogeneity. On the other hand, they point out that GIS can easily resolve this problem by producing reliability maps which indicate areas where the data may or may not be used with confidence.

Theocharopoulos *et al.* (1995) suggested that an advantage of GIS is its ability to allow data to be easily updated. Weir (1991) concluded that GIS achieves the efficient automation of the translation of soil data into soil information.

2.6.2 Terrain analysis

2.6.2.1 Quantitative terrain analysis

Digital elevation models (DEM) are one way that GIS quantitatively describe landscape surfaces. Dymond and Luckman (1994b) defined DEM as a two dimensional array of points of which each represents an elevation value.

Digital elevation data may be represented one of two ways, as a grid DEM or as triangular irregular networks (TIN) (Walsh, 1989). Grid DEM are regular arrays of elevation values that represent the shape of the land surface (Petersen *et al.*, 1995). More specifically, DEM comprise a list of x, y, and z coordinates that are stored in a computer file. They may represent the land surface or some other surface such as a water-table (Dymond, 1995). The main source for the production of contour, slope and aspect maps is a DEM (Chang and Tsai, 1989). Within a GIS, thematic maps can be draped over the DEM to present results more realistically (Theocharopoulos *et al.*, 1995). DEM may be derived from aerial photographs, topographic maps, or satellite images (Gallant *et al.*, 1996).

The automated extrapolation of soil-landscape models to areas outside those in which the models were developed, requires the use of DEM. Therefore, DEM are essential for increasing soil-landscape model utility (Petersen *et al.,* 1995). However, DeRose (1994) believed that until methods for delineating landforms from DEM are properly developed, the extrapolation of predicted soil classes would be difficult.

The application of soil-landscape models using DEM allows for the semi-automation of soil survey (Hewitt, 1993). The most important applications of DEM in soil-landscape modelling include the three-dimensional display of landscapes, model simulation, sample site selection, the delineation of slope and aspect maps, acting as a template over which thematic maps may be draped, and the delineation of soil-landscape units (Burrough, 1986; Hammer *et al.,* 1991; Dymond, 1995). McKenzie *et al.* (1996) stated that a strong emphasis must be placed on associated pedological and geomorphic processes in order for the full potential of terrain analysis in soil survey to be realised.

The development of three-dimensional soil-landscape models involves the use of GIS and the determination of landscape attributes via DEM analysis. Many algorithms have been devised to calculate terrain attributes from DEM. These attributes describe the topographic characteristics of the landscape and are indicative of the spatial distribution of some soil processes. Primary terrain attributes include slope, aspect, elevation, slope plan curvature, slope profile curvature, flow path lengths, and catchment area. Secondary attributes include wetness index, stream power index, and transport capacity index. These primary and secondary attributes are used in the prediction of soil property spatial distribution (Moore *et al.,* 1993b; Dymond and Luckman, 1994b; McSweeney *et al.,* 1994; Odeh *et al.,* 1994; Odeh *et al.,* 1995; Dymond, 1995; Gessler *et al.,* 1995; Petersen *et al.,* 1995; Irvin *et al.,* 1997).

The explicit, efficient, and quantitative characterisation of the landscape is achieved by digital terrain analysis. Such analysis can also identify the mass and energy fluxes in order to describe pedogenesis and the resulting profile morphology (McSweeney *et al.,* 1994). Thus, it could be said that terrain analysis involves the assessment of terrain attributes derived from a DEM and is used for the prediction of the spatial distribution of soil properties (Gessler *et al.*, 1995; Petersen *et al.*, 1995). Dymond and Luckman (1994b) predicted soil classes from DEM attributes by using simplified rule induction. The resulting soil map was compared with a conventional soil map. The predicted map was found to have an accuracy of between 60% and 80%. It was concluded that DEM attributes alone were enough to predict soil classes (Dymond and Luckman, 1994b).

2.6.3 Pedometrics: the quantification of soil spatial variability

To achieve improvements in the usefulness and quality of soil information, the issue of soil variability must be considered (Petersen *et al.*, 1995). Understanding variability is the central purpose of the discipline of statistics (Upchurch and Edmonds, 1991). Therefore, soil variability may be described and analysed via the use of conventional statistical and geostatistical techniques. Such techniques can transform complex variable soil data into useful descriptions allowing for the prediction of soil property values at unvisited sites (Webster and Oliver, 1990). The application of statistical procedures to the quantification of soil spatial variability began in the early 1960s (Wilding and Drees, 1983).

2.6.3.1 Definition and approaches

'Pedometrics' has been defined as "the application of probability and statistics to soil" (Webster, 1994, p. 1). More specifically, it refers to "the quantitative study of the variation of field soil" (Burrough *et al.*, 1994, p. 311). Courtney and Nortcliff (1977) believed the use of statistical techniques in the study of soil distribution is related to the simplification of relationships between different soil classes or properties, or between environmental (state) factors and soil properties.

2.6.3.2 Conventional statistics

The quantitative analysis of soil data may be conducted using a wide range of conventional statistical techniques such as principle component analysis, correlation analysis, numerical classification, multiple regression, canonical analysis, and ANOVA (Dent and Young, 1981). The most appropriate technique(s) to use is largely dependent upon the nature of the data set (Upchurch and Edmonds, 1991).

Measures of the position of a distribution (mean, median, and mode) provide a useful starting point in the analysis of soil property variability. The mean is particularly useful but may be influenced by outliers in the data set. In such situations, the median may be more useful. Measures of the dispersion of a data set, such as the range, standard deviation, and the variance, can also be very useful (Webster and Oliver, 1990).

A common measure used in the expression of soil property variability is the coefficient of variation (CV) which is simply the ratio of the standard deviation to the mean, and expressed as a percentage (Dent and Young, 1981). For the comparison of the variability of soil properties, CV can be a meaningful and useful measure. However, when there is covariance between the mean and standard deviation its use may be invalid (Wilding and Drees, 1983).

Analysis of variance may be employed to compare the means of two or more sets of soil data provided a number of assumptions can be met. The purpose of using ANOVA in a soil survey context is to determine significance of differences between data sets (usually representing soil classes or map units). Nested ANOVA designs can be used to partition within-map-unit variability into its various sources (Upchurch and Edmonds, 1991).

2.6.3.3 Geostatistics

Geostatistical techniques are those statistical techniques that do not require the data to be spatially independent. The geostatistical techniques discussed below serve the primary purpose of predicting property values at unvisited locations (interpolation) but may also be used to estimate the mean and variance of a population (Upchurch and Edmonds, 1991) and to design optimal sampling schemes. Burrough *et al.* (1994) stated that geostatistics provides an appropriate theoretical framework for the study of soil variability.

Regionalised variable theory

The assumption underlying geostatistical techniques is that the spatial variability of soil properties can be described "by a continuous random, but spatially correlated stochastic field" (Burrough, 1993, p. 537). In geostatistics, variables such as soil properties are referred to as regionalised variables. Regionalised variables are spatially dependent – that is, their values are related to location (Wilding and Drees, 1983). According to the regionalised variable theory, soil spatial variability can be expressed in terms of three main components: (1) a deterministic function which describes the structural variability at a given point; (2) a stochastic, spatially dependent residual component; and (3) a random, spatially independent component. It is assumed that variance of differences depends solely on the distance separating locations. This difference is known as the semi-variance. In essence, the differences between locations are simply a function of the distance between them. A graph in which semi-variance is plotted against distance (lag) is called a semi-variogram (Figure 2.3) and may represent an initial step towards the quantitative description of variability (Burrough, 1983).

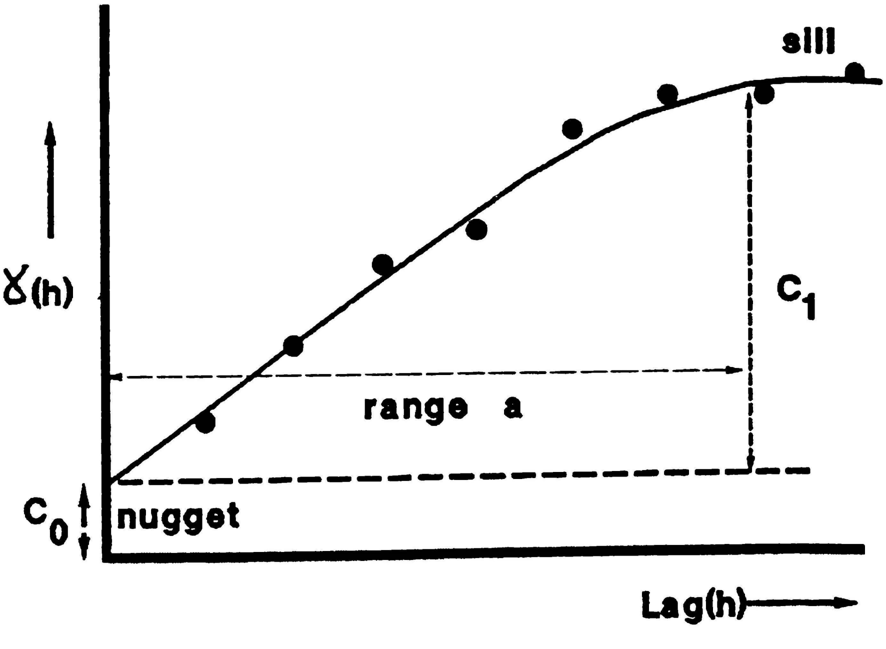

Figure 2.3. An example of a semi-variogram fitted using a spherical model (From: Burrough, 1993, p. 540).

The semi-variogram is very useful as it provides information for spatial prediction, the optimisation of sampling designs, and for the determination of spatial patterns. The important characteristics of the semi-variogram (Figure 2.3) include: (1) the sill, which represents the value of maximum variance in the data and is the sum of the structural and random components of variability; (2) the range, which is the distance over which a property is spatially dependent and at which the semi-variance reaches a maximum; and (3) the nugget (y-intercept) represents very short-range variability and the random variability resulting from measurement errors (Wilding and Drees, 1983; Burrough, 1993).

Rahman *et al.* (1996), in their study of the spatial variability of forest soils in the Medicine Bow Mountains of Wyoming, made use of both conventional statistics and geostatistics. The conventional statistical techniques used were principle component analysis, CV, and correlation and regression analysis. Both linear and spherical models of the semi-variogram were employed to describe the spatial variability. Rahman *et al.* (1996) found that geostatistics was useful for elucidating the nature of soil property variability whereas conventional statistics were not.

2.6.3.4 Applications of pedometrics

Daniels and Hammer (1992) were sceptical of the wholesale adoption of geostatistical procedures. They suggested that geostatistics should be used only as a supplement to detailed field investigations and that all existing knowledge about soil-landscape should be considered when designing experiments. Furthermore, in order for data to be transferable between landscapes, sampling designs and techniques should take stratigraphic, geomorphic, and hydrologic conditions into account. The correct interpretation of statistical data requires an understanding of landscape systems (Daniels and Hammer, 1992). On the other hand Gerrard (1990) suggested that the use of geostatistical tools is essential for evaluating hill-slope variations in soils.

Sources of soil spatial variation can be partitioned according to their spatial scale of operation by using the multivariate, geostatistical tool, factorial kriging analysis (FKA). This tool is used in association with expert knowledge regarding pedogenic processes. Such an analysis allows for the major sources to be mapped and for the examination of soil property correlation at individual spatial scales (Dobermann *et al.*, 1995).

Assessment of soil spatial variability

Initial assessments of within-map-unit variability consisted only of estimates of taxonomic purity. Later, statistical techniques were applied to the assessment of within-map-unit variability (Courtney and Nortcliff, 1977).

Nordt *et al.* (1991) investigated the within-map-unit variability in Brazos County, Texas, using binomial probability and conventional statistical techniques (means, standard deviations, and confidence limits). They found that the purity of the map units was less than suggested by the survey report. Nordt *et al.* (1991) recommended that soil survey reports should contain tables of data quantifying map unit composition probability in order to increase the confidence with which land management decisions could be made.

Assessment of quantitative soil-landscape relationships

Almost since the founding of pedology, pedologists have been attempting to mathematically establish the relationships between the soil forming factors and soil properties (Birkeland, 1999). The traditional approach to assessing soil-landscape relationships, which involves relating soils to somewhat arbitrarily-defined geomorphic units in addition to using regression analysis to quantify soil-topography relationships, is unsatisfactory according to Gerrard (1990).

Florinsky and Arlashina (1998) adopted a quantitative approach to the assessment of relationships between micro-topographic features and the morphology of Vertisols in Russia. Such an approach involved the quantification of several terrain attributes: aspect, slope steepness, elevation, specific catchment area, plan curvature, profile curvature, mean curvature, stream power index, and compound topographic index. Topographic index is an estimate of water accumulation whereas stream power index describes the potential of overland flow to erode. These terrain attributes were derived from a DEM. The relationships between the terrain attributes and the soil properties of interest were determined using linear correlation analysis. The combination of terrain attributes that best described the relationships were selected using step-wise linear regression. It is not possible to rely on the findings of previous studies when selecting which terrain attributes to study because the relative importance of various terrain attributes differs between landscapes. Therefore, it is necessary to begin by investigating a wide range of terrain attributes (Florinsky and Arlashina, 1998). The quantification and use of terrain attributes accounted for 82% of the variability in B horizon depth. Variability in horizon depths was best explained by stream power index, specific catchment area, and topographic index. Horizon depths were influenced to a lesser extent by plan curvature, profile curvature, mean curvature (Florinsky and Arlashina, 1998).

Chen *et al.* (1997) assessed the differences between geomorphic positions using ANOVA and Duncan's test. Soil-topography relationships were determined using a linear multivariate technique called redundancy analysis (RDA). The Monte Carlo permutation test was used to determine which landscape variables accounted for the most soil variation. Hairston and Grigal (1991) employed ANOVA to assess differences between soil properties and geomorphic positions also. Probability plots were used to assess the distributions of the data. Brubaker *et al.* (1993) located a 20 m by 65 m plot within each of six geomorphic positions at four sites in agricultural croplands. The soil was sampled at three locations and at six depth intervals within each plot. In the statistical design, the sites provided the replicates. Carter and Ciolkosz (1991) studied the effect of slope steepness and aspect on soil formation and properties. Soil profiles were described along two transects extending down slopes of opposite aspects from a common summit area. Relationships were assessed using linear regression. Hairston and Grigal (1994) made observations along down-slope transects at each aspect within four randomly located training windows. The significance of differences in soil property values between aspects, plan curvatures, and geomorphic positions were determined using ANOVA. Enoki *et al.* (1996) placed a 4 m by 4 m grid over a hill-slope and measured the elevation at each point. Every second point of the grid was then sampled. The mean value of the measured soil properties of each geomorphic unit was calculated and the differences between the geomorphic units were assessed using ANOVA. Feldman *et al.* (1991) assessed the relative utility of soil physical, chemical, mineralogical, and morphological for differentiating between morphologically similar soils at different locations using multiple discriminant analysis.

GIS and pedometrics

A GIS may be used to calculate the statistical descriptors of soil property data (such as the mean, variance, and semi-variance). The statistical descriptors may then be used to conduct interpolation, design sampling schemes, or to simulate within-map-unit soil property variability (Burrough, 1991).

Geostatistics could be used to incorporate a measure of observed soil spatial variability into GIS analysis and soil mapping (Burrough, 1991; Rogowski and Wolf, 1994). McBratney (1992) reported that geostatistical techniques are the obvious choice for soil property prediction in GIS. Burrough (1986) suggested that errors involved in GIS map analysis may be reduced when within-map-unit variability is determined by interpolation. He also stated that a good GIS should contain a number of interpolation techniques. It is worth noting that, despite its popularity, kriging is not the only method of spatial interpolation and is not necessarily the most appropriate in every case (Palmer *et al.*, 2004).

2.7 Mapping soils using soil-landscape modelling

In an attempt to meet the soil information requirements of land managers (e.g. forest managers), the soil-landscape relationships that were used implicitly in conventional soil surveys are now being made explicit (Hewitt, 1993; Moore *et al.*, 1993a; Gessler *et al.*, 1995; Jones, 1998; Hill, 1999) in the form of soil-landscape models. Soil-landscape modelling is a relatively new approach to soil survey and differs from conventional soil survey in that the survey methodology and the reporting of results is focussed on large scale soil-landscape relationships rather than on broad patterns of soil class distribution alone.

2.7.1 Introduction to soil-landscape modelling

Soil-landscape modelling involves the development of predictive relationships between soil classes or properties (response variables) and observable landscape features (explanatory variables) for the purpose of predicting and mapping soil spatial distribution across the landscape (Hewitt, 1994). Therefore, soil-landscape modelling can be used to provide soil spatial information for land resource management and can also facilitate an understanding of the dynamic spatial patterns within a landscape (Hewitt, 1994; Thwaites and Slater, 2000). Soil-landscape modelling is one of the main applications of predictive modelling in soil survey, which has, in the past, been neglected. Soil-landscape models are conceptual, empirical, and predictive models (Hewitt, 1993).

The main advantages of soil-landscape modelling are discussed by Bell *et al.* (1992). Soil-landscape models help the pedologist to interpret and organise information on landscapes, determine consistent soil-landscape relationships, and make field work more efficient. Hewitt (1993) suggested that soil survey efficiency may be improved by soil-landscape models. Trangmar (1994) stated that the costly field work component of soil survey could be conducted more rapidly – and by implication more cheaply – using soil-landscape modelling. On comparing conventional soil survey and soil-landscape modelling, it is evident that soil-landscape modelling allows for the consideration of more landscape variables and in a more quantitative and consistent way (Bell *et al.*, 1992). The quantification of soil-landscape relationships is necessary in order to improve our understanding of them. Such quantification is a central aim of modern pedology (Petersen *et al.*, 1995). Some advantages of making soil-landscape models explicit include satisfying the requirements of the scientific method, increasing survey efficiency, and recording the expertise of pedologist (Hewitt, 1994). Soil-landscape models should represent field processes and take into account three dimensional soil-landscape relationships (Hall and Olson, 1991). Therefore, they may be used to provide the detailed, three-dimensional information on soil spatial distribution that is required for the spatial application of pedogenic models (Slater *et al.*, 1994).

It has been a long-recognised concept in pedology that the improved representation of soil-landscapes must result in a better understanding of soil spatial information. However, the necessary data organisation and analysis tools have not been available to until relatively recently (McSweeney *et al.*, 1994). Soil-landscape modelling studies can generally be assigned to one of two broad approaches: (1) qualitative soil-landscape modelling and (2) quantitative soil-landscape modelling. The key difference between these approaches is that quantitative soil-landscape modelling makes use of quantitative soil-landscape relationships whereas qualitative soil-landscape modelling does not. Each will be considered below following a discussion of the methodology generally applicable to both approaches.

2.7.2 General soil-landscape modelling methodology

The focus of soil-landscape modelling methodology is the development of a set of soil-landscape relationships. These relationships can then be used to predict the distribution of soil classes or properties across the landscape.

Five main steps in the development of soil-landscape models are generally recognised: (1) integration of data on the soil forming factors; (2) landscape characterisation (identification, description, and delineation of geomorphic features or derivation of terrain attributes); (3) collection and spatial referencing of soil data; (4) formulation of the relationships between the soils and landscape features (e.g. landscape units or terrain attributes); (5) extrapolation of soil-landscape relationships to predict soil classes or properties across the landscape (application of the model); and (6) testing of predictions (model validation). Steps 2, 3, and 4 are typically conducted within small training areas, sometimes referred to as 'training windows' (McKenzie and Austin, 1993; Lynn and Basher, 1994b; McSweeney *et al.,* 1994; Harmsworth *et al.*, 1995; Hewitt, 1995; McLeod *et al.,* 1995).

Fritsch and Fitzpatrick (1994) proposed a slightly different method for developing qualitative soil-landscape models. Their 'pedo-hydrological' approach placed greater emphasis on understanding landscape hydrology in relation to the development of soil-landscape relationships. The method relates soil-water processes to the variation in soil morphology along a toposequence. Tonkin (1994) described how the concepts of geomorphology, soil geomorphology, and soil stratigraphy can and should be applied to the development of soil-landscape models.

A method for determining the representativeness of training windows (reference areas), called the 'mathematical soilscape distance', was presented by Lagacherie *et al.* (2001). The 'soilscape' (soil-landscape unit) distance is a measure of the difference in soil-forming factor class (e.g. landform unit, parent material unit) frequencies between the reference area and points within the wider surrounding region. The soilscape distance measure can also be used to help determine the optimal location and size of training windows when planning a new survey (Lagacherie *et al.*, 2001).

2.7.2.1 Assessing soil-landscape relationships

Soil-landscape modelling relies heavily, but not exclusively, on the prediction of soil distribution from landscape features that can be readily observed. In the majority of landscapes, geomorphic factors and vegetation cover are the most readily observable landscape features. Climatic factors are not often employed because significant climatic variation is unlikely within the area of a land system. Also, most climate-related soil differences are often associated with changes in geomorphic factors (e.g. elevation or aspect). Relating soil distribution to vegetation is of limited usefulness because many landscapes are no longer covered with native vegetation (Chen, 1997). Although it is recognised that Leathwick *et al.* (2003) developed a national numerical ecosystem classification based largely on analyses of the environmental relationships or 'drivers' of common New Zealand tree species. Therefore, most soil-landscape studies tend to focus on the relationships between soils and topography (Irvin *et al.*, 1997). However, the importance of understanding the relationships between the soils and the other soil forming factors, in the development of soil-landscape models, should not be underestimated. The fact that, in any given landscape, not all soil properties are related to topography necessitates the investigation of the relationships between soils and the other soil forming factors, especially parent material, and the incorporation of these relationships into soil-landscape models. In the development of soil-landscape models, soils are most commonly related to topography and parent materials (Chen, 1997).

2.7.3 Qualitative soil-landscape modelling

The qualitative approach to soil-landscape modelling generally involves the spatial prediction and mapping of soil classes (general purpose or local classifications) using either qualitatively (most common) or quantitatively defined landscape units (e.g.

Agbu *et al.*, 1989; McIntosh, 1994; Trangmar, 1994; Hewitt, 1995; McLeod *et al.*, 1995; Jones, 1998; Hill, 1999). Qualitative soil-landscape models can also be used to predict soil properties from qualitatively- or quantitatively-defined landscape units (e.g. McIntosh *et al.*, 2000; Young and Hammer, 2000) or mapped soil classes (soil-landscape units) (e.g. Lagacherie and Voltz, 2000). These models could be termed 'semi-quantitative' soil-landscape models because they predict quantitative soil property values. The spatial prediction of soil properties from qualitatively-defined landscape units, soil-landscape units, or soil classes may also be referred to as the 'class-based' approach to soil property prediction.

Landscape units are commonly based on geomorphic factors such as landform, relative landscape position, slope shape, slope steepness, and aspect (e.g. McLeod *et al.*, 1995). However, other observable landscape features such as vegetation type (Rahman *et al.*, 1997) or land use (Webb and Burgham, 1997) may also be incorporated into the landscape unit definitions. The observable landscape features used in the development of qualitative soil-landscape models are usually qualitatively defined and arranged according to the land systems approach (section 2.7.3.1 below). However, some studies have used quantitatively defined units (e.g. landscape units derived from the classification of a DEM) (e.g. Dymond and Luckman, 1994b).

Qualitative soil-landscape models may be developed, applied, and presented with the assistance of a GIS (Rahman *et al.*, 1997) or a DEM (Harmsworth *et al.*, 1995; McLeod *et al.*, 1995), or both. Rahman *et al.* (1997) concluded that GIS-assisted soil-landscape modelling is a useful tool for locating probable soil boundaries when conducting detailed soil mapping. McLeod *et al.* (1995) found that although the soil-landscape model they applied using a DEM was slightly less accurate than the more detailed model they applied manually at the same scale (1:50 000), the DEM allowed for a considerable saving in time. The embodiment of qualitative soil-landscape relationships in the form of a soil-landscape 'key' can allow for the conceptual soil-landscape framework developed in one area to be transported and successfully applied to a similar land system in a different area (McIntosh and Hunter, 1994).

Validation tests show that well-developed soil-landscape models can predict the spatial distribution of soil classes with considerable accuracy. For instance, studies conducted in New Zealand and Papua New Guinea (Trangmar, 1994; Hewitt, 1995; McLeod *et al.* 1995; Rijkse and Trangmar, 1995) have reported success rates in excess of 80% particularly when predicting broad soil classes (i.e. order or group levels) at large scales. Accurate qualitative soil-landscape models can provide a very useful framework – in the form of their landscape or soil-landscape units – for the subsequent spatial prediction of soil properties (Webb and Burgham, 1997). Significant differences in the mean soil property values calculated for each unit may be found (McIntosh *et al.*, 2000; Young and Hammer, 2000) and if so, the mean values can then be spatially applied (predicted) using the landscape or soil-landscape unit map.

2.7.3.1 The land systems approach

The land system approach is a method of landscape classification and subdivision (King, 1970). A land system generally corresponds to an area in which there is a recurring pattern of vegetation, topography, and soils under a relatively uniform climate (Christian and Stewart, 1952). A land system may also be defined to be the area of validity of a soil-landscape model. In New Zealand, the land systems approach is the recommended approach for the development of qualitative soil-landscape models (Lynn and Basher, 1994a). King (1970) suggested that land systems should be characterised using a set of mainly topography-related parameters such as geomorphic process, elevation, geology, drainage network pattern, slope shape, and geomorphic position.

The land systems approach, introduced by Christian and Stewart (1952), has been used for land resource surveys in Australia and Papua New Guinea since the late 1940s (Bleeker and Speight, 1978; Dalal-Clayton, 1988). Using the land systems approach, soil distribution is mapped via the extrapolation of relatively few observations relating soils to landscape units. It is assumed that the relationships between soils and landforms or vegetation are strong enough to provide predictions (Bleeker and Speight, 1978). Soil-landscape units are delineated mainly on the basis of topographic (landform) features arranged in a hierarchical framework (Briggs and

Shishira, 1985). However, patterns of vegetation may also be taken into account (Bleeker and Speight, 1978). The emphasis on landforms can be justified because they: (1) can be identified and delineated relatively easily; (2) are an expression of the interaction of the other environmental factors; (3) are usually permanent features; and (4) are typically strongly related to soil conditions. Despite such justifications, doubts still remain as to the strength of validity of this approach (Briggs and Shishira, 1985). However, Briggs and Shishira (1985) concluded that areas with different soil properties can generally be identified by delineating landscape units. Moreover, Briggs and Shishira (1985) stated that at least some soil variability will always be accounted for by the geomorphic subdivision of the landscape. However, the accurate interpretation of soil-geomorphic relationships is essential if the land systems approach is to be successfully applied (Gerrard, 1990).

The land systems approach was originally used for reconnaissance soil surveys. However, the methodology has been readily adapted for use in the development and application of qualitative soil-landscape models at large scales. Three units corresponding to different hierarchical levels (Table 2.1) are often delineated: (1) the land system; (2) land components; and (3) land elements (Lynn and Basher, 1994a). Soil-landscape model validation, which is the systematic assessment of model predictions, may also be facilitated by the land systems approach (Harmsworth and Dymond, 1994).

Table 2.1. Definitions, scale, and examples of proposed hierarchical levels for the mapping of land systems in New Zealand (From Lynn and Basher, 1994a, p. 43).

Term	**Definition**	**Example**	**Scale**
Land Province	major geomorphic zone, an assemblage of surface forms expressive of large scale lithological association(s)	Axial mountains and associated intermontane basins	1:500,000 - 1:1,000,000
Land Region	geomorphic zone, macrorelief unit	mountain range, lowland plains	smaller than 1:250,000
Land System	recurring pattern of topography, soil dominance, and vegetation with a relatively uniform climate **and** the area of validity of a given predictive soil-landscape model	floodplains, fans; sand dune complex; glacial moraine/outwash complex; soft rock hill slopes, etc	1:50,000 - 1:100,000
Land Component	genetically uniform with similarity of age and surface materials	terrace tread, terrace riser; stable summit, backslope, footslope, etc	1:10,000 - 1:50,000
Land Element	area between break or inflection in slope	upper backslope, microdune, channel, bar, etc	larger than 1:10,000

2.7.4 Quantitative soil-landscape modelling

Quantitative soil-landscape modelling predominantly involves the spatial prediction and mapping of individual (target) soil properties using quantitative and continuously varying terrain attributes or quantitatively-defined landscape units (e.g. McKenzie and Ryan, 1999; Florinsky *et al.*, 2002; Hengl *et al.*, 2004; Shi *et al.*, 2004). However, soil classes may also be predicted using some quantitative soil-landscape modelling techniques (e.g. Thomas *et al.*, 1999; Lagacherie and Voltz, 2000; Carré and Girard, 2002; Kravchenko *et al.*, 2002). Soil property (and class) predictions are made by the developing and applying quantitative soil-landscape relationships (McKenzie and Austin, 1993). A range of techniques exist for formulating these relationships and making the predictions (i.e. for developing and applying quantitative soil-landscape models). The techniques can be arranged into two groups:

(1) statistical techniques and (2) hybrid techniques (McBratney *et al.*, 2000). The latter group of techniques represent the combination of statistical and geostatistical approaches — hence the term 'hybrid'. The main techniques comprising each group are discussed below.

2.7.4.1 Statistical techniques

Regression-based predictions

The relationships between soil properties (or property indices) and continuously varying, quantitative terrain attributes (derived from a DEM) are commonly determined and applied using a stepwise multi-linear regression (MLR) technique (Moore *et al.*, 1993a; Bell *et al.*, 1995; Tomer and Anderson, 1995; Tomer *et al.*, 1995; Thompson *et al.*, 1997; Gessler *et al.*, 2000; Johnson *et al.*, 2000; Chaplot *et al.*, 2001; Florinsky *et al.*, 2002; Chaplot *et al.*, 2004). Stepwise regression allowed for the selection of the optimal set of terrain attributes to predict a given soil property (Johnson *et al.*, 2000). Linear regression has also been used to relate soil properties to quantitative terrain attributes that have been classified using fuzzy logic (e.g. de Bruin and Stein, 1998; Lark, 1999). In these studies the soil properties are related to the transformed membership values of the continuous (fuzzy) classes. In some cases, the use of generalized linear models (GLM) may be more appropriate than classical MLR — when predicting binary soil properties or predicting from discrete explanatory variables, for instance (McKenzie and Austin, 1993; Gessler *et al.*, 1995; McKenzie and Ryan, 1999). Park and Vlek (2002) found that the prediction performance of GLM was better than that of decision (regression) trees. Campling *et al.* (2002) used a form of GLM called logistic modelling to predict the distribution of soil drainage classes from terrain attributes and satellite imagery. They found that this technique correctly predicted the drainage class at the majority of validation points (>60%).

Regression-based techniques have been shown to generally provide reasonably accurate soil property predictions, with the terrain attributes often explaining more than 50% of the variability in soil properties (Tomer and Anderson, 1995; Thompson *et al.*, 1997; de Bruin and Stein, 1998; Lark, 1999; Gessler *et al.*, 2000; Chaplot *et al.*, 2001). However, some studies have reported less successful predictions (e.g. Johnson *et al.*, 2000). Also, Florinsky *et al.* (2002) found that soil property predictions made using landscape units based on accumulation, transit, and dissipation zones can be more effective than those made using regression. They pointed-out that the temporal variability of some soil properties may mean that regression-based predictions are relevant for a limited period of time. The fuzzy classification of terrain attributes can improve the predictive performance of regression-based techniques (de Bruin and Stein, 1998; Lark, 1999).

Knowledge-based predictions (expert systems)

Quantitative soil-landscape models may be applied via the use of expert systems (artificial intelligence), which express soil-landscape relationships mathematically as a set of rules (e.g. Skidmore *et al.*, 1991, 1996; Dymond and Luckman; 1994a; Cook *et al.*, 1996; de Bruin *et al.*, 1999; Zhu, 1999; Wielemaker *et al.*, 2001; Corner *et al.*, 2002). The rules are used to predict the probability of occurrence of soil properties in a given area. The soil-landscape relationships behind the predictions can be made explicit allowing for reproducibility (Cook *et al.*, 1996). Some studies have applied a fuzzy inference approach, called the soil-land inference model (SoLIM), to express soil spatial distribution in the form of continuous soil property maps (Zhu *et al.*, 1997; Zhu *et al.*, 2001). More recently, the soil-landscape relationships have been expressed in the form of specific cases using case-based reasoning (Shi *et al.*, 2004).

Pedologists have long applied their knowledge and experience of the factors of soil formation and soil-landscape relationships to interpret and delineate soil units (Skidmore *et al.*, 1991). However, expert systems make this experience and knowledge available to others (Luckman *et al.*, 1990), especially via their association with GIS (Cook *et al.*, 1996). Expert systems may be used to access, analyse, and interpret soil information (Luckman *et al.*, 1990) and may also facilitate the production of more accurate soil maps (Skidmore *et al.*, 1996). According to Skidmore *et al.* (1991), expert systems provide one of the best means for the quantitative application of the state factor model to soil survey.

The pedologist's knowledge and experience can be converted into rules and stored in a GIS (Skidmore *et al.*, 1991). Expert systems and GIS may be integrated in a number of possible ways (Luckman *et al.*, 1990). One way of creating rules is by rule induction (Luckman, 1994). These rules may then be applied to the analysis and interpretation of various sets of data, also within the GIS, for the purpose of identifying/delineating soil-landscape units. For example, these data might be in the form of maps of the factors that affect the distribution of soils. Using the spatial information held in the GIS, the soil-landscape unit or soil property most likely to occur at each point is inferred by the expert system (Skidmore *et al.*, 1991). Therefore, expert systems are a means by which soil-landscape models are applied in a GIS context. Skidmore *et al.* (1991) described the rules of an expert system as the link between the pedologist and the GIS databases. More recently, Wielemaker *et al.* (2001) described a methodological framework in which a pedologist's landscape knowledge could be formalised. The methodology involved the arrangement of landforms into a nested hierarchy before the knowledge rules were inferred and formalised within a GIS. Wielemaker *et al.* (2001) argued that this approach allows for more efficient use of the knowledge applied by the pedologist in conducting a soil survey and commonly contained within the survey report.

Skidmore *et al.* (1991) found that the map of soil-landscape units produced using an expert system had an accuracy of 66.7%. They stated that its accuracy could be improved by incorporating more relevant data layers into the GIS. Skidmore *et al.* (1996) found that the soil map produced using an expert system was slightly less accurate than the conventional soil map. They considered it was sufficiently, accurate, however, to be operational. In contrast, Shi *et al.* (2004) found their case-based reasoning approach to be more accurate than conventional soil mapping. Zhu *et al.* (1997, 2001) found that the SoLIM provided soil property predictions at least as accurate as for conventional soil maps and that this approach is potentially more efficient (in terms of time and money) than conventional soil survey.

Other statistical techniques

Several other statistical techniques have been used to relate soil properties to terrain attributes for the purpose of predicting soil properties.

Some studies have used decision trees to predict soil properties and classes from terrain attributes (Cialella *et al.*, 1997; McKenzie and Ryan, 1999; Henderson *et al.*, 2004). Decision trees are developed by progressively separating soil data into increasingly uniform sub-groups using the explanatory variables (e.g. terrain attributes) and can incorporate both discrete and continuous explanatory variables and predict either soil properties (regression trees) and classes (classification trees) (McKenzie and Ryan, 1999). A reasonable proportion of the variability in some soil properties can be explained using decision trees (McKenzie and Ryan, 1999; Henderson *et al.*, 2004). Cialella *et al.* (1997) were able to predict soil drainage classes with reasonable (78%) precision also.

Soil classes (mainly soil drainage classes) have been predicted from explanatory variables using discriminant analysis by some workers (Bell *et al.*, 1992, 1994; Thomas *et al.*, 1999; Kravchenko *et al.*, 2002). Discriminant analysis selects the optimal set of explanatory variables for differentiating between soil classes and then identifies the class most likely to occur at unvisited points (where only the explanatory variables are known) using a classification function or decision rule (Bell *et al.*, 1992; Kravchenko *et al.*, 2002). Soil class predictions made using discriminant analysis have generally been found to be reasonably accurate in comparison to conventional soil maps with some studies reporting correct predictions in excess of 70% of validation points (e.g. Bell *et al.*, 1992; Kravchenko *et al.*, 2002). A conditional probability approach (proposed by Lagacherie *et al.*, 1995) has also been used to predict soil classes from explanatory variables (Lagacherie and Voltz, 2000). This approach works on the assumption that the soil class at an unvisited point is dependent on the soil classes at surrounding points and the difference in elevation and distance between points. Soil classes were more accurately predicted using this approach than they were with conventional soil mapping (Lagacherie and Voltz, 2000). Another study predicted soil class distribution from terrain attributes using a maximum likelihood classification technique and also obtained reasonably precise predictions (Boer *et al.*, 1996).

In a study undertaken in New Zealand (Lynn *et al.*, 2002), tables of soil property trends were mathematically interpolated using terrain attributes (elevation and aspect) derived from a DEM. The predictive performance of this model was moderate (it explained 47% of the variability in topsoil pH).

Principle component analysis has been applied in combination with multi-linear regression (e.g. Gobin *et al.*, 2001). Gobin *et al.* (2001) found that performing principle component analysis on the terrain attributes before constructing the MLR models improved predictive performance.

2.7.4.2 Hybrid techniques

Regression-kriging

Regression-kriging is an example of a hybrid soil spatial prediction technique which has been applied and investigated by several studies (Odeh *et al.*, 1994, 1995; Bishop and McBratney, 2001; Carré and Girard, 2002; Hengl *et al.*, 2004). It combines MLR with geostatistical interpolation (ordinary kriging). Regression-kriging can be performed several different ways. For instance, Odeh *et al.* (1994, 1995) described three regression-kriging models: models A, B, and C. Model A simply involved the multi-linear regression of soil properties with explanatory variables (e.g. terrain attributes) at development points followed by the interpolation of the predicted values from the development points to unvisited (i.e. validation) points using ordinary kriging. In model B, the MLR prediction residuals (difference between observed and predicted values) were interpolated from the development points to unvisited points, in addition to the MLR-predicted values, and the two values were summed to give final predictions. In model C, the MLR prediction residuals were interpolated from the development points to unvisited points and were then summed with the predictions made at the unvisited points using MLR to give final predictions (Odeh *et al.*, 1994, 1995). Carré and Girard (2002) used regression kriging (model C) to predict continuous soil classes from terrain attributes and satellite imagery. Taxonomic distances, which describe the degree of separation between the soil at a given point and the central concept of the class, were correlated to the explanatory variables and extrapolated using multi-linear regression and kriging was used to interpolate the residuals of the regression.

Regression-kriging has been shown by some studies to generally perform better than other soil spatial prediction techniques (both quantitative soil-landscape modelling and geostatistical) such as MLR, ordinary kriging, universal kriging, and co-kriging (Odeh *et al.*, 1994, 1995; Hengl *et al.*, 2004). Moreover, Odeh *et al.* (1994) indicated that regression kriging was particularly useful for soil properties that are weakly correlated to terrain attributes. However, one study found that kriging with external drift (see below), MLR, and generalised additive models generally performed better than regression-kriging (Bishop and McBratney, 2001). Continuous soil classes were predicted with only moderate success using regression kriging (Carré and Girard, 2002).

Kriging with external drift and co-kriging

Soil properties can be predicted with the aid of explanatory variables such as terrain attributes or remote sensing data using certain types of geostatistical interpolation which include kriging with external drift and co-kriging (Leenaers *et al.*, 1990; Bourennane *et al.*, 1996, 2000; Chaplot *et al.*, 2000a, 2000b; Bourennane and King, 2003; Mueller and Pierce, 2003). Kriging with external drift is a form of universal kriging which makes use of readily measured explanatory variables to assist in the prediction (interpolation) of a soil property based on sparse observations of that property. It is assumed that linear relationships exist between the soil property being predicted and the explanatory variables (Bourennane and King, 2003). The explanatory variable is described as a regionalized variable and is used as an external drift function (Bourennane *et al.*, 1996).

Kriging with external drift has been found to generally give more precise soil property predictions than universal kriging, co-kriging, kriging with a trend model, (multi-)linear regression, and ordinary kriging (Bourennane *et al.*, 1996, 2000; Bourennane and King, 2003; Mueller and Pierce, 2003). Furthermore, Bourennane and King (2003) demonstrated that the use of two explanatory variables (slope steepness and electrical resistivity) resulted in more precise predictions than when only one or other of the explanatory variables were used. Mueller and Pierce (2003) found that, on a 61-m regular sampling grid, the quantitative soil-landscape modelling techniques they examined (kriging with external drift, multi-linear regression, and co-kriging) gave more precise predictions than the purely geostatistical techniques (ordinary kriging and kriging with a trend model). In other studies, co-kriging was shown to provide more precise soil property predictions that multi-linear regression (Leenaers *et al.*, 1990; Chaplot *et al.*, 2000a, 2000b).

2.8 Mapping soils using spatial interpolation

2.8.1 Principles and theory

Soil property values at un-sampled points can be interpolated from sampled points in order to map the distribution of a given property or to describe the within-map-unit variability (Burrough, 1991). Interpolation is often conducted using geostatistics. Information that can be used for optimal interpolation (kriging) is contained by semi-variograms (Burrough, 1991). Moreover, semi-variograms form the basis of the kriging method of interpolation because they are used to determine the optimal weights for interpolation (Burrough, 1993). More specifically, they describe the way that soil properties vary in space. Soil properties can be predicted for any un-sampled point within a map unit if the variogram is known. Within a GIS framework, a variogram for each important soil property could be stored as attribute data and linked to each polygon of a soil map (Burrough, 1991).

2.8.2 Interpolation methods and sampling designs

McBratney (1992) stated that geostatistical methods of interpolation are superior to other methods. However, he conceded that sampling to determine the variogram still presents a challenge. Geostatistical interpolation is different from other interpolation techniques in that the weightings used in the prediction are derived from geostatistical spatial analysis as opposed to deterministic spatial functions. There are several different kriging techniques that can be applied to the prediction of soil properties: point, block, universal, disjunctive, indicator, and co-kriging. Point and block kriging are both ordinary kriging methods. The non-geostatistical interpolation techniques include inverse distance weighted, trend surface analysis, splines, and Thiessen polygons (Burrough, 1993). The kriging techniques are the most commonly used interpolation techniques in the Earth Sciences. However, the inverse distance weighted technique is also used (Myers, 1994; Palmer *et al.*, 2004).

Gotway *et al.* (1996) compared the accuracy of the ordinary kriging and inverse distance weighted methods of interpolation for mapping soil properties in Buffalo County, Nebraska. The inverse distance method performed well when the property being mapped had a CV less than 25%. However, at high distance powers, it tended to be inaccurate for properties with higher CV values. The performance of kriging was found to be unaffected by the variability of the properties. The accuracy of kriging was generally high and thus was found to be the preferable technique. The inverse distance method has the advantage of being easily applied (Gotway *et al.*, 1996; Palmer *et al.*, 2004).

The results of interpolation are commonly presented as raster or isoline maps, often within a GIS framework. When kriging is used, the prediction errors can also be presented as maps which provide information regarding the reliability of the interpolated soil property maps (Burrough, 1991, 1993).

2.9 Summary

Soil spatial variability results from spatial changes in the soil forming factors across the landscape. This soil variability is, in the most part, systematic, anisotropic, complex, continuous, and variable with scale. Moreover, different soil properties vary differently.

Conventional soil survey, coupled with a general purpose soil classification system, attempts to rationalise soil variability by partitioning the landscape into discrete, supposedly homogenous map units containing one or more taxonomic units. The intention of soil survey is to identify areas of land that can be managed differently (Beckett and Webster, 1971). In association with a soil map and survey report, general purpose soil classification is the vehicle by which the collected soil information is communicated to the land manager.

The nature of the soil information required by land managers, such as forestry companies, has changed. Information on the magnitude, distribution, and variability of soil properties, important to land management decision making, is required. Furthermore, land managers require this information to be quantitative, precise, of a large scale, and presented in flexible formats including a measure of reliability.

It is widely recognised in the literature that conventional soil survey is not adequately meeting the new soil information requirements. The reasons for the inadequacy of conventional soil survey include: (1) the large, generally unreported within-map-unit variability; (2) a reliance on taxonomic classes; (3) the high costs of mapping at large scales; and (4) the lack of reliability assessments.

Pedometrics, the quantitative study of soil variability, represents a set of conventional statistical and geostatistical techniques that can be used to predict soil property values, to describe property variability, and to quantify the level of confidence that can be achieved in predicted data.

Geographic information systems (incorporating DEM) represent a set of spatial data management and analysis tools that facilitate the quantitative development and application of soil-landscape models. Together with pedometric techniques, GIS also allows for the spatial interpolation and analysis of soil properties. In addition, GIS provides for flexibility in the collation, manipulation, and presentation of soil information.

Research into soil-landscape modelling, a relatively recent approach to soil survey, is currently being conducted in an attempt to meet the new information requirements of land managers. Soil-landscape modelling may allow for large scale soil surveys to be conducted more effectively with regard to time and cost. Soil-landscape modelling, when supported by the GIS, terrain analysis, and pedometrics, can provide quantitative soil information in a more flexible and explicit manner. There is an extensive body of literature relating to soil-landscape relationships and the development of soil landscape models in New Zealand and overseas. However, little research has been conducted into the suitability and performance of soil-landscape modelling methodology when used in plantation forest environments.

Clearly, there is a paucity of research on the applicability and suitability of the soil-landscape modelling approach to plantation forestry environments. Moreover, in New Zealand, the forestry industry is seeking the most appropriate means of collecting and communicating the soil information it requires. Therefore, there is a both a scientific and practical need to evaluate the appropriateness of soil-landscape modelling for collecting the soil information required for forest management.

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CHAPTER THREE

Southern Mahurangi Forest: location, environment, and management history

3.1 Introduction

This chapter describes the location, environment, and management history of southern Mahurangi Forest. Soils and the landscapes in which they occur evolve over time under the influence of several natural environmental factors (Jenny, 1941, 1980) and are also influenced by the land management activities of people (Bidwell and Hole, 1965; Fanning and Fanning, 1989). Therefore, an examination of the natural environmental factors is required to fully understand the nature of the soils of southern Mahurangi Forest and their relationships to the landscape. Furthermore, an examination of the history of land use and forest management activities is needed to understand the impacts of forest harvesting on the soils and soil-landscape relationships.

The chapter begins with the description of the study site location. The natural environmental factors governing the evolution of the landscape and soils of the forest over time are then examined in detail and the existing information relating to the soils of the forest is reviewed and redefined. The history of land use and forest management is considered and finally, all information regarding the study site environment is summarised.

3.2 Study site location

The study was conducted within southern Mahurangi Forest (Redwoods and Watson's Blocks), an exotic, *Pinus radiata*-dominated plantation forest, owned and managed by Carter Holt Harvey Forests Ltd. Southern Mahurangi Forest is situated approximately 5 km south of Warkworth on the Northland Peninsula (northern Auckland region), North Island, New Zealand (Figure 3.1).

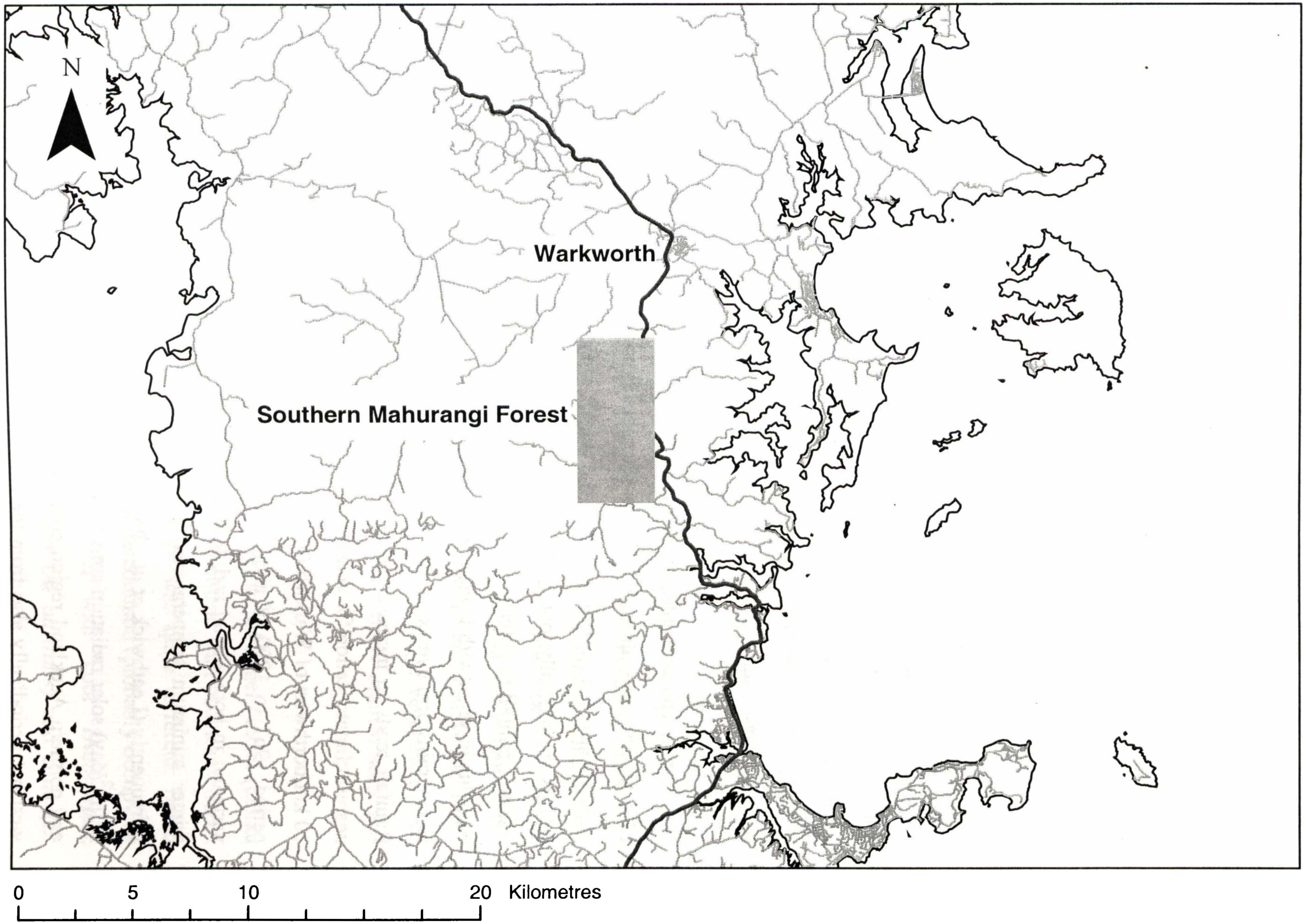

Figure 3.1. Map showing the location of southern Mahurangi Forest

3.3 Natural environmental factors

Four broad environmental factors (climate, native vegetation, parent material, and topography/geomorphology) operate over time to control soil and landscape evolution (Jenny, 1941). The factors are discussed below, each in turn.

3.3.1 Climate

The climate of Northland and northern Auckland can be described generally as warm and moist with mild winters (Harmsworth, 1996; Leathwick *et al.*, 2003). It should also be noted that the climate of the region has been relatively mild in comparison to the rest of New Zealand since the Last Interglacial at least (Ballance and Williams, 1992; Newnham, *et al.*, 1999), although mean annual temperatures were up to ~ 4 °C colder and conditions were substantially drier (and probably more fire-prone) during the Last Glacial (Newnham, 1999; Sandiford *et al.*, 2002; Newnham *et al.*, 2004).

The average annual rainfall in the vicinity of Mahurangi Forest over the period 1961 to 1990 was about 1 600 mm (Tomlinson and Sansom, 1994a). Rainfall usually reaches a maximum during the winter months. Although annual water deficits are generally low (≤ 46 mm), the low (≤ 3.4) monthly water balance ratio (ratio of rainfall to potential evaporation) tends to make the region susceptible to droughts in years with lower than average rainfall (Leathwick *et al.*, 2002, 2003). Heavy rainstorm events are not uncommon between late-spring and mid-autumn. Rainfall tends to increase with increasing elevation (Harmsworth, 1996). The nearest climate station for which reliable temperature data exists is at Leigh, some 20 km northwest of Warkworth, which had an average annual temperature for the period 1961 to 1990 of about 15 °C (Tomlinson and Sansom, 1994b). The variation in both annual and daily temperatures is low (Harmsworth, 1996) and winter minimum temperatures are high (~ 6 °C) with frosts occurring only infrequently (Leathwick *et al.*, 2003). Annual (~ 15 $MJ/m^2/day$) and winter (~ 6 $MJ/m^2/day$) solar radiation are very high (Leathwick *et al.*, 2003). The Northland and northern Auckland region commonly receives winds from the southwest or west but periodically also from the southeast or northwest (Harmsworth, 1996). Fong (2001) found no substantial aspect-related differences in evaporation from pastured slopes in the Mahurangi area. The lack of a strong relationship between evaporation and slope aspect was attributed to the predominance of cloudy days in the area (Fong, 2001).

3.3.2 Native vegetation

Two small remnants of native forest currently exist in close proximity to the study site, one to the north of Moirs Hill and the other to the south of the study site. The remnants have been mapped and described by Clarkson and Clarkson (1993) as rimu-taraire-tawa dominated broadleaf-conifer forest. The rimu-taraire-tawa forest class is characterised by a mixture of hardwoods, dominated by tawa (*Beilschmiedia tawa*) and taraire (*Beilschmiedia tarairi*), throughout which the larger rata (*Metrosideros robusta*) and rimu (*Dacrydium cupressinum*) trees are scattered. Commonly abundant subordinate species are rewarewa (*Knightia excelsa*) and kohekohe (*Dysoxylum spectabile*). Other species present include pukatea (*Laurelia novae-zelandiae*), puriri (*Vitex lucens*), tree ferns (*Cyathea* spp. and *Dicksonia* spp.), hinau (*Elaeocarpus dentatus*), and miro (*Prumnopitys ferruginea*). Large kauri (*Agathis australis*) trees were very rare and towai (*Weinmannia silvicola*) have a minimal presence (Clarkson and Clarkson, 1993; Leathwick *et al.*, 2003). Puketea and kahikatea probably occupied gully-floor channels. The few kauri trees present, together with the other conifers, most likely grew on the less fertile soils on the ridge summits and upper back-slopes whereas the more fertile middle to lower back-slopes and gully-floors were dominated by the broadleaf species (Wardle, 1991; Burns and Leathwick, 1996; Leathwick *et al.*, 2003). In deforested areas, rush and sedge vegetation often occurs in association with, and is thus indicative of, poorly drained soils and landscape positions (Harmsworth, 1996).

During the Last Glacial, the forest cover probably remained largely intact (unlike areas south of Auckland that were dominated by shrubland with patches of beech and conifer-broadleaf forest) but compositionally was quite different: beech *Nothofagus* (probably *N. truncata*) was much more common (probably occupying nutrient deficient soils and dry ridges), together with 'cool' *Halocarpus*, *Libocedrus*, and *Phyllocladus* species, but kauri (*A. australis*) and rimu (*D.*

cupressinum) were essentially absent (Ogden *et al.*, 1993; Newnham, 1999; Sandiford *et al.*, 2003; Newnham *et al.*, 2004).

3.3.3 Geology and parent materials

The rocks, from which the soil parent materials of the study site were weathered, were deposited during the Early Miocene and so the following discussion is focussed on the geology of that period. The parent rocks (of the soils) were mapped as the thickly bedded, alternating, volcanic-rich sandstones and siltstones of Pakiri Formation (Waitemata Group) (Edbrooke, 2001). The stratigraphy and hierarchical arrangement of lithologies in the vicinity of the study site is summarised below (Figure 3.2).

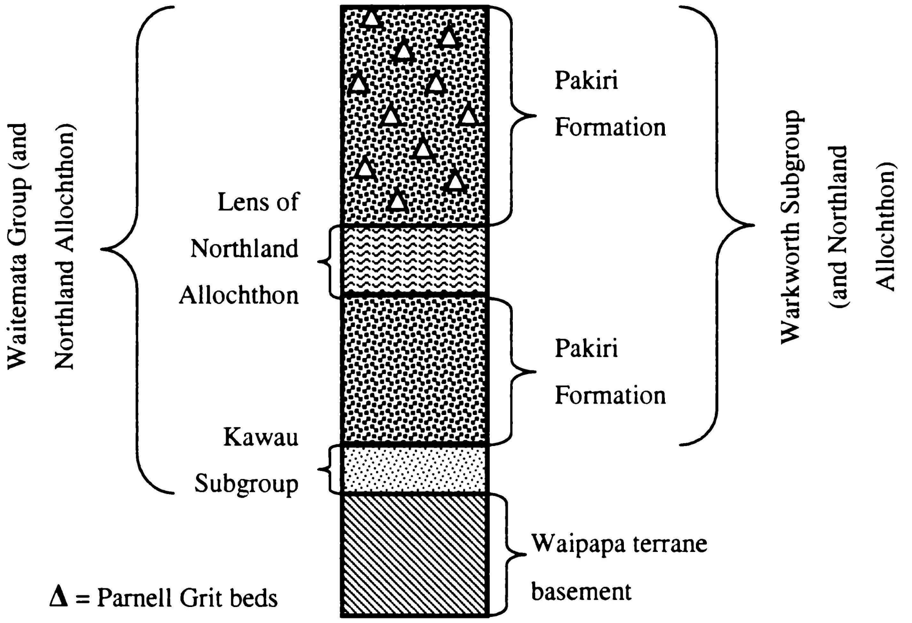

Figure 3.2. Simplified stratigraphy in the vicinity of the study site (adapted from Isaac *et al.*, 1994, 103).

3.3.3.1 Geology of the Early Miocene

The nature of the Early Miocene geology of Northland and northern Auckland was influenced by the subduction of the Pacific Plate beneath the Australian Plate (Isaac *et al.*, 1994). More specifically, subduction-related volcanism and compressional tectonism acted in concert with the emplacement and subsequent south-eastern migration of the Northland Allochthon to influence the Early Miocene geology of the region (Edbrooke, 2001).

Waitemata Group rocks represent the sediments deposited within the Waitemata Basin. The formation of the Waitemata Basin began in the Early Miocene, soon after the initiation of subduction (Hayward, 1993). Bounding the basin to the east and west were two calcalkaline volcanic belts (identified as the eastern and western volcanic belts, respectively). Blocks of uplifted basement (Te Kuiti Group overlying Waipapa terrane basement) border the basin to the north and the south (Ballance, 1974). The Waitemata Basin received sediment from the western volcanic centres, the Waipapa terrane, and the recently emplaced Northland Allochthon (Hayward and Smale, 1992). An unidentified source also contributed sediments to the southern part of the basin (Raza *et al.*, 1999). Underlying the Waitemata Group is the Waipapa terrane in the east (Spörli, 1978), the autochthonous Te Kuiti Group in the south, and the Northland Allochthon in central and north-western areas (Ballance and Spörli, 1979).

Forming the base of the Waitemata Group is the Kawau Subgroup that was deposited in a shallow marine environment during the early Otaian (Hayward and Brook, 1984). A change in depositional environment from coastal and shallow marine to mid-bathyal depths occurred as a result of rapid subsidence in the early Otaian (Ricketts *et al.*, 1989; Isaac *et al.*, 1994). After the subsidence, turbidity currents entered the basin from the northwest forming the thick bathyal flysch (alternating sandstone and mudstone) deposits of the Warkworth Subgroup which overlie the Kawau Subgroup (Ballance, 1976; Isaac *et al.*, 1994). Contemporaneously, nappes of the Northland Allochthon moved into the basin from the north (Isaac *et al.*, 1994). The Waitemata Group has been considerably deformed probably because it was partially deposited on the Northland Allochthon, which was still in motion. Intensive faulting and folding of the Waitemata Group is common. During the most recent episode of deformation, a change from northwest-southeast to northeast-southwest extension occurred (normal faults trended first northeast then northwest). The horst and graben topography of Northland resulted from this extensional faulting. Moreover, the pattern of faults is a product of the rifting that occurred during Cretaceous to Oligocene. All deformation of the Waitemata Group occurred prior to the Pliocene (Spörli, 1989).

The rocks of the Warkworth Subgroup have been subdivided into several formations on the basis of stratigraphic or geographic differences (Edbrooke, 2001). Of these, it is the Pakiri Formation, comprising thickly bedded, volcanic-rich, turbidites, which occurs at the study site (Edbrooke, 2001). In eastern areas, the Pakiri Formation overlies the Kawau Subgroup conformably (Isaac *et al.*, 1994).

The Pakiri Formation comprises 10–30-m thick parcels of graded, medium- to coarse-grained, turbiditic sandstone (beds usually 1–4 m thick) interspersed with thinner deposits (beds usually 0.05-0.2 m thick) of laminated siltstone and fine-grained sandstone (Hayward, 1993; Isaac *et al.*, 1994; Edbrooke, 2001). Argillaceous and volcanic grains co-dominated the lithic sandstones (Ballance, 1974). Also, the sandstones of the Pakiri Formation have coarser textures and are thicker than the volcanic-poor formations of the Warkworth Subgroup (Hayward, 1993). Near to the study site, the sediments of the Pakiri Formation are predominantly of Early Miocene volcanic (andesitic, basaltic, and dacitic) origin. However, the Mangakahia, Motatau, and Tangihua complexes of the Northland Allochthon also contributed a substantial amount of sediment. Thus, volcanogenic clinopyroxene is the dominant heavy mineral with magnetite, hornblende, and ilmenite being subordinate. Zircon, titanite, and epidote are also present (Hayward and Smale, 1992). Underwater gravity flows of volcaniclastic material, known as Parnell Grit, are interbedded throughout many of the Waitemata Group turbidite sediments including the Pakiri Formation (Ballance and Gregory, 1991; Isaac *et al.*, 1994; Allen, 2004). The Parnell Grit deposits probably occur near the base of the Pakiri Formation in the vicinity of the study site (to the east) but in western areas they occur nearer the top and are more common (Isaac *et al.*, 1994; Edbrooke, 2001). Lenses or disrupted thrust wedges, derived from the southward advancing nappes of the Northland Allochthon, are also contained within the Pakiri Formation (Kear and Waterhouse, 1977; Hayward, 1987; Edbrooke, 2001). The lenses, known as Onerahi Chaos-breccia, represent submarine gravity slide deposits and are made up of blocks of various Paleogene lithologies suspended in a matrix of soft Eocene mudstone (Hayward, 1987).

The Parnell Grit beds in the north and west (enveloped by volcanic-rich and mixed flysch) were probably derived from the slopes (volcanic apron) of the western volcanic centres protruding above sea level (Balance and Gregory, 1991; Allen, 2004) whereas those in the southeast (enveloped by volcanic-poor flysch) were derived from volcanoes to the north or east (Allen, 2004). The Kaipara volcano is the source of the Parnell Grits contained within the upper Pakiri Formation (Hayward and Smale, 1992). Beds of Parnell Grit typically contain clasts of andesitic and basaltic lava, fragments of crystals, pumice clasts, flysch rip-up clasts, fossils of shallow-marine origin, and rounded igneous pebbles in a sand and clay matrix (Ballance and Gregory, 1991; Allen, 2004). However, both within- and between-bed variations in lithology are substantial (Ballance and Gregory, 1991). Furthermore, the composition of the beds is associated with their location within the basin and the enveloping turbidite sediments (Allen, 2004). In the north and at shallow depths the beds are dominated by thick conglomerates whereas the beds at greater depths and in central basin locations are finer grained (Allen, 2004). Beds can be up to 30 m thick (Isaac *et al.*, 1994) and commonly their upper parts are composed of medium- to coarse-grained sandstone (Ballance, 1974). Invariably the beds are coarser grained, contain more volcanogenic material, and are thicker than the sandstones enveloping them (Ballance, 1974). Another ubiquitous feature of the beds is the inverse-to-normal size grading (Ballance and Gregory, 1991). The Parnell Grit has a similar suite of heavy minerals to that of the surrounding Pakiri Formation: clinopyroxene is dominant and magnetite is subordinate (Hayward and Smale, 1992). The deposition of Parnell Grit beds occurred much less frequently than the deposition of the turbidites. However, it is likely that they were voluminous (Ballance and Gregory, 1991).

The sediments of the Waitemata Basin underwent shallow burial prior to the current surface being exposed and, as a result, burial temperatures were not greater than 60 °C (Raza *et al.*, 1999).

3.3.3.2 Geology of the Middle Miocene to Holocene

After the active plate boundary departed to the south in the Middle Miocene, the Northland Peninsula became strongly eroded as the result of uplift in the east leading to tilting towards the west (Isaac *et al.*, 1994). The region has been relatively tectonically inactive, however, since around the beginning of the Pliocene (Evans, 1994). The area in which the study site is located may have been a terrestrial environment exposed to sub-aerial weathering and erosion cycles for the last 16.5 Ma (since the Middle Miocene). The weathering of the surficial Pakiri Formation deposits in a generally warm and moist though droughty climate under essentially continuous forest cover over a long period of time has produced a ubiquitous, thick, clay-rich (saprolite) regolith mantle (Ballance and Williams, 1992).

3.3.3.3 Soil parent materials

The majority of the soils within southern Mahurangi Forest were formed from clay-rich saprolite (an in situ weathering product) derived from the volcanic-rich sandstones and siltstones of the Pakiri Formation (Waitemata Group). Other soils were formed from materials derived from the reworking (colluvial or alluvial) of the saprolite (Rijkse, 1996). Mass-movement processes (e.g. mudslides) have transported the saprolite material down-slope where it has accumulated on foot-slopes or in gully-floors as colluvium (section 3.3.4.1). A reasonably substantial proportion of the soils in the forest are likely to have been formed from the colluvial material (although it is difficult to distinguish the colluvial material from the in situ saprolite). Eroded saprolite material has also entered the network of streams and, after being transported further down-stream, has been deposited as alluvium adjacent to the major stream channels (Rijkse, 1996). The colluvial materials deposited in the gully-floors as mudslides probably represent a major source of the alluvium because the streams would subsequently erode into these deposits (Brunsden, 1984). Only a relatively small proportion of soils in study site are likely to have formed from the alluvial material. Another very small proportion of soils were formed directly from relatively weakly weathered Pakiri Formation rocks where such rocks have been exposed in recent times. Also, it is possible that in some very rare instances the Parnell Grit may be a soil parent material.

Occasional additions of distal, thin, fine-grained tephra material to the soils of the forest are probable because numerous such ash-grade tephra beds (ranging from ~ 1 to ~ 100 mm in thickness) have been recorded both to the south and north of the study area in lake deposits (Shane and Hoverd, 2002; Sandiford *et al.*, 2003;

Newnham *et al.*, 2004). As well, volcanic glass and volcanic quartz have been recorded in some soils in Northland (Fields and Weatherhead, 1968; Mizota, 1982; Stewart *et al.*, 1986). It is most likely that the thin tephra deposits were either incorporated into the topsoil via pedoturbation or were washed down-slope to become mingled with the alluvium (Cox, 1973). Aeolian dust from Australia probably has been added in small amounts to the land surface, and assimilated into the soils on stable sites (upbuilding pedogenesis) (Windom, 1969; Chen *et al.*, 1985; Stewart *et al.*, 1986; Hesse, 1994; Eden and Hammond, 2003).

In northern Auckland, the saprolite regolith thickly mantles almost the entire landscape and can extend to depths of 30 m below the land surface (Markham and Crippen, 1981). Two broad types of saprolite, differentiated on the basis of colour, are recognised: reddish (red-weathered) and yellowish-brown (non red-weathered). The origin of the red-weathered saprolite has been the subject of much speculation but had not previously been directly investigated (Cox, 1973). The predominant view was that the reddish saprolite was formed as the result of weathering during the warmer periods of the Pleistocene or possibly as early as the Tertiary. However, some researchers have suggested that hydrothermal activity may be responsible (Cox, 1973). The colouration of the reddish saprolite can be attributed largely to the presence of the crystalline Fe-oxide mineral haematite (Schwertmann, 1993) (other reddish Fe-oxides such as ferrihydrite may also be present). The materials in which haematite has formed during the weathering processes are referred to as 'red-weathered' in this thesis. A rich source of iron, free-drainage, a warm climate, an almost neutral pH, and fast organic matter turn-over are the prerequisites of haematite formation during weathering (Schwertmann and Taylor, 1989; Kämpf *et al.*, 2000). It has been suggested that the transformation of the reddish saprolite into yellowish-brown subsoils during the soil evolution may occur via the migration of haematite down the profile (Cox, 1973).

3.3.4 Geomorphology and topography

The geomorphology in the general vicinity of the study site was largely influenced by block faulting in the Late Cenozoic (Edbrooke, 2001). Moreover, the nature of the geomorphology, topography, and soils of the Northland and northern

Auckland region as a whole has, to a great extent, been influenced by the nature of the underlying lithologies (Harmsworth, 1996).

The study site is situated within the Mesozoic-Cenozoic highland physiographic unit (land region) according to the terrain classification of Schofield (1988). Four distinct landform assemblages (land systems), each associated with a different broad lithology, have been identified within the Mesozoic-Cenozoic highlands. Of these, the study site is located within the stream-incised, gently rolling to very steep, hill country land system which is formed in the Cenozoic sedimentary deposits (Waitemata Group) overlying basement rocks (Kermode *et al.*, 1992; Edbrooke, 2001). This hill country land system generally corresponds to the undulating to very steep (Cenozoic) sedimentary-rock physiographic unit (Land Use Capability [LUC] suite 4) described by Harmsworth (1996). More specifically, the study site falls within the interbedded sandstone and mudstone (flysch) land-type (LUC sub-suite 4a) of Harmsworth (1996). According to the environmental domain classification "Land Environments of New Zealand" developed by Leathwick *et al.* (2003), much of the study area falls within the Level II class A6 (undulating hills of the Northern Lowlands Environment). However, some of the more elevated parts fall within the Level II class D1 (rolling hills of the Northern Hill Country Environment) (Leathwick *et al.*, 2002, 2003).

Much of the hill country land system is fairly subdued and strongly dissected with only moderately steep slopes because there are few beds in the Waitemata Group that are resistant to weathering and erosion. However, in the vicinity of the study site (areas north of Waiwera), the resistance to erosion was greater due to the more volcanic-rich nature of the lithology (Pakiri Formation). The greater resistance lead to the formation of steeper slopes (mostly strongly rolling to steep) and higher ridges (Ballance and Williams, 1992; Harmsworth, 1996; Edbrooke, 2001). Furthermore, the scarp-and-dip-slope terrain, steep cliffs, and waterfalls to the north of Waiwera have formed as a consequence of the thick and gently dipping sandstone deposits of the Pakiri Formation (Ballance and Williams, 1992).

At a larger scale, Rijkse (1996) identified three broad geomorphic units within Mahurangi Forest: (1) hill summits and slopes, (2) gully-floors, and (3) minor alluvial flats. The hill summits and slopes geomorphic unit is the most common within the forest and was further subdivided into three sub-units on the basis of slope steepness: (1) flat to rolling land (0-15°), (2) strongly rolling to moderately steep land (16-25°), and (3) steep to very steep land (26-35°). Narrow valleys are common due to the hilly nature of the landscape. The floors of the gullies have, in many instances, become fairly flat and broad due to the accumulation of colluvium in the form of mudslide deposits (Rijkse, 1996; Moon *et al.*, 2003) — see below. Adjacent to some of the larger streams, alluvial deposits form relatively small, flat, alluvial flood-plain surfaces. Water tends to accumulate and persist in these low-lying parts of the landscape (Rijkse, 1996). Elevations within the study site range from a low of about 20 m to a local high of 358 m (Moirs Hill) but for the majority of the study site the elevation range is 100-300 m above sea level (Department of Lands and Survey, 1981).

Slope instability is prevalent in the vicinity of the study site due to the combination of the thick, clayey regolith and strongly rolling to steep slopes (Ballance and Williams, 1992). Moreover, much of the land on which Mahurangi Forest is now located has experienced erosion to some degree in the past (possibly accelerated while it was under pasture). The establishment of the pine forest possibly slowed the rate of erosion (Rijkse, 1996) but this relationship is speculative. Erosion potential in the area is considered to be moderate to severe (Harmsworth, 1996; Rijkse, 1996). Suspended sediment yields for the study area, estimated using GIS modelling and upscaling by Hicks *et al.* (2003), are mapped at a relatively modest ~ 50-200 t/km^2/yr (Hicks and Shankar, 2003). The type of, and potential for, erosion is mainly controlled by soil/regolith wetness, slope steepness, soil permeability, and degree of rock weathering (Harmsworth, 1996). The main forms of erosion (particle and mass movement) that have been found to occur in the hill country land system are mudslides (earthflows), slumps, translational landslides, tunnel gully, soil/earth slips, and sheet erosion (Harmsworth, 1996; Rijkse, 1996; Moon *et al.*, 2003). Mass movement events generally occur on slopes above 15° to 25°. On the less steep (< 18°) lower back-slopes and foot-slopes, tunnel gully erosion can occur in the Whangaripo and Puhoi soils (Harmsworth, 1996).

3.3.4.1 Mudslides (earthflows)

Moon *et al.* (2003) found that mudslides (shallow and fairly slow-moving mass movement features) were overwhelmingly the most common form of soil mass movement on the Tawharanui Peninsula (near to the study site). The Tawharanui Peninsula lies within the same land system as southern Mahurangi Forest and so its geology and soils are very similar also. It is evident that mudsliding has been, and still is, a significant geomorphic process within the study site.

Mudslides have been defined as mass movement features that occur in soft, weak and fine textured soil or regolith materials (Brunsden and Ibsen, 1996; Moon *et al.*, 2003) such as the clay-rich soils and saprolites at the study site. Three main components of mudslide morphology are recognised (Figure 3.3): (1) a cirque-like source area, (2) an elongated flow of material (track), and (3) a lobate zone of accumulation (Brunsden, 1984; Moon *et al.*, 2003). Source areas are characterised by steep headwalls, various slips, failures, or slumps and areas of complex debris deposition. The depressions sometimes contained within source areas are commonly wet (Brunsden, 1984). The flow-paths are often straight and well defined but may be influenced by the morphology of the landscape into which the material is flowing (Brunsden, 1984; Moon *et al.*, 2003).

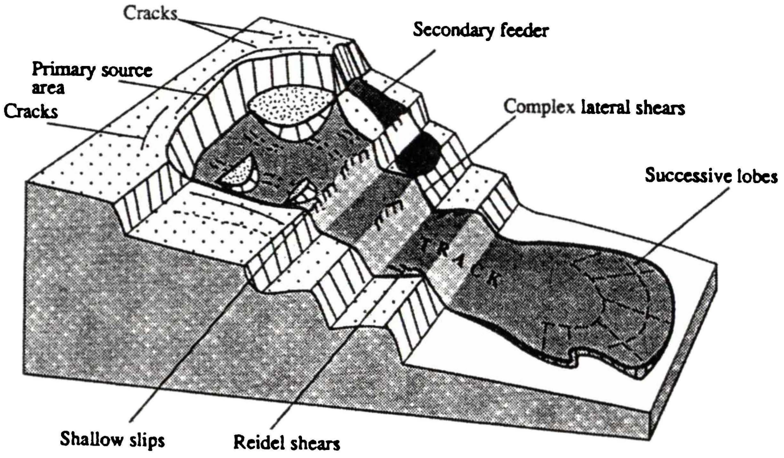

Figure 3.3. Common mudslide morphology (from Brunsden and Ibsen, 1996). The structural benches shown are not related to the morphology of the mudslide.

Moon *et al.* (2003) suggested that the shallow, circular failure of saturated soil and saprolite materials at the bedrock-regolith contact (basal shear surface) is the mechanism by which mudsliding occurs in the Tawharanui-Mahurangi area. The moderately well developed structure of topsoils allows for the infiltration of water into the profiles whereas the clayey textures of the subsoil and saprolite materials lead to slow permeability which, in turn, leads to the saturation of much of the regolith for significant periods of time. The combined effect of the frequent saturation with the low regolith shear strength has resulted in the propensity for mudslides to occur where slope angles attain 15° to 20° in the Mahurangi area (Moon *et al.*, 2003).

Small to relatively large, intact, 'blocks' of hill-slope may have broken away from the rest of the slope in the source areas of some of the mudslides in southern Mahurangi Forest and were transported amongst the loose material down the path of the flow to be deposited in a lower part of the landscape as mound-like features (V. Moon, 11 September, 2002, personal communication). The source areas of the old, stabilised, mudslides may now appear as flattish, bench-like features set into the hill-slopes. The common occurrence of these bench-like features within the slopes of the Mahurangi area was noted by McClean (1995). She indicated that the benches were not controlled by geological bedding and suggested that they were mass movement-related features.

3.3.4.2 Topography and soil drainage

Strong relationships between soil drainage and topography have been identified in the Northland and northern Auckland regions (Cox, 1988). Soil drainage is considered to be influenced by several geomorphic and hydropedologic factors including landscape position, slope steepness, soil permeability, and water table height. For instance, the soils of flat areas in the lower parts of the landscape are often found to be near saturation for much of the year and are consequently poorly drained (Cox, 1988). The relatively high rainfall in the region means that a considerable proportion of the soils will exhibit some signs of periodic saturation.

3.4 The soils of southern Mahurangi Forest

The soils of Northland and northern Auckland are special within New Zealand because of the co-incidence of several factors including a warm, generally moist climate with very high solar radiation, fairly easily weathered rocks, unique indigenous forest associations, an absence of thick tephra deposits, a lack of glacial erosion, relatively old landforms, and a fairly subdued topography (Gibbs *et al.*, 1964; Orbell *et al.*, 1980; Molloy, 1998; Ballance and Williams, 1992; Harmsworth, 1996). They are also seen as important historically because N.H. Taylor developed in Northland some of his ideas for genesis-based soil classification, and around 25% of the "Soils of New Zealand" reference sites are in Northland (N.Z. Soil Bureau, 1968). The aforementioned factors have resulted in the evolution of soils that are generally clayey, strongly weathered, relatively strongly leached, usually infertile, and have thin topsoils. Soils formed from recent alluvium or on steep eroding slopes are exceptions to the above characteristics (Gibbs *et al.*, 1964; Yeates *et al.*, 1981). Previously, much emphasis has been placed on the influence of indigenous vegetation on the formation, characteristics, and distribution of the soils in Northland and northern Auckland (e.g. Gibbs *et al.*, 1964). The idea that forest composition controlled the degree of soil leaching was considered to be of such importance that previous soil investigations in the region have arranged the soil continuum into a framework based largely on differences in leaching (i.e. leaching sequences within a suites of soils formed from similar parent materials) (Orbell *et al.*, 1980; Sutherland *et al.*, 1980).

Most of the soil series described below are part of the Puhoi suite (Sutherland *et al.*, 1980), meaning that they formed on similar parent materials (Waitemata Group materials) and are thus of a similar age if in a similar landscape position. The two series not belonging to the Puhoi suite are the Kara and Whakapara soils which are mainly formed from alluvial (and colluvial) material (Whareora suite). Two new series ('Pohuehue' and 'Hungry Creek') are proposed to encompass the soils found within the study area that do not correlate with any of the existing series. The Pohuehue series would be best placed within the Puhoi suite whereas the Hungry Creek series would fit best within the Whareora suite based on the parent materials of these soils. The climate under which all the series formed is also likely to be similar (fairly warm and generally moist). The series of the

Puhoi suite were intended to represent a leaching sequence from the weakly to moderately leached Puhoi and Atuanui soils to the strongly leached Warkworth soils. It was thought that the leaching differences were caused by compositional differences in the native forest (the more kauri trees that were present the more enleached the soils were expected to be).

Given the overlap among series and the many inconsistencies and inaccuracies in the unit-sheet descriptions, the appropriateness of partitioning the soil continuum (in the Mahurangi area at least) on the basis of leaching differences is questionable. Furthermore, it is now recognised that some of the more weakly leached members of a suite tend to be poorly drained whereas the moderately to strongly leached members are better drained (Cox, 1988). That is, nutrients are removed from the drier soils in the upper parts of the landscape and subsequently accumulate in the wetter lower landscape positions. An exception to the above relationship would be some of the Atuanui soils formed on the steeper and (sometimes) drier hill-slopes, which are necessarily less leached due to the lack of profile development (Harmsworth, 1996) rather than impeded drainage. In some areas (such as the Mahurangi area) the soils of some suites may be better considered in terms of a drainage sequence driven by topographically controlled water movement (the landscape hydrology). Although a leaching sequence may exist, in some landscapes it is likely to be the consequence of drainage rather than vegetation differences. Rijkse (1996) considered the differences in the soils of Mahurangi Forest to be related to profile drainage, topographic position, and degree of profile development (weathering).

3.4.1 Redefinition of previously identified and mapped soil series

Rijkse (1996) described and mapped the soils of Mahurangi Forest at a scale of 1:15 000. The soil taxonomic framework adopted by Rijkse (1996) was, in part, based on that used in the original 1:100 000 soil survey of the region, conducted between 1937 and 1951 (by N.H. Taylor, A.C.S. Wright, and C.F. Sutherland), and most recently published as Sutherland *et al.* (1980). Rijkse (1996) correlated the soils of the forest with the previously defined soil series of the area and classified them using the New Zealand Soil Classification (NZSC) (Hewitt, 1993). The series that occur within the forest are summarised (Table 3.1) and described below. Most are reinterpreted and redefined because of inconsistencies and errors identified in some previous reports. Also, the two newly proposed series are described and discussed.

Table 3.1. Summary of redefined and proposed soil series, their classification (NZSC), some characteristics (drainage and leaching), and related environmental factors (parent material and landscape position) (Sutherland *et al.*, 1980; Rijkse, 1996; Clayden *et al.*, 1997)[1].

Soil Series	NZSC†[2]	Drainage class‡	Degree of leaching[3]	Parent material	Landscape position[4]
Warkworth	UYT	WD to MWD	Strongly leached to weakly podzolised	Reddish or yellowish saprolite (Pakiri Fm.)	Upper & Middle-High/Divergent
Whangaripo	UYM	ID	Moderately to strongly leached	Reddish or yellowish saprolite (Pakiri Fm.)	Upper, Middle-High/Divergent/ Convergent
Puhoi	UYM	SPD	Weakly to moderately leached	Yellowish saprolite (Pakiri Fm.)	Lower & Middle-Low/Convergent
Atuanui	ROA & ROM*	WD to SPD	Weakly to moderately leached	Reddish or yellowish saprolite (Pakiri Fm.)	Upper & Middle-High/Convergent
Pohuehue§	UPT	PD to VPD	Weakly leached	Yellowish saprolite (Pakiri Fm.)	Lower
Kara	GOJ*	PD to VPD	Weakly leached	Saprolite derived alluvium/colluvium	Lower (including mudslide feature benches)
Whakapara	RFMA* & WF*	SPD	Weakly leached	Saprolite derived alluvium	Lower (gully-floors)
Hungry Creek§	WGT & WGF	PD to VPD	Weakly leached	Saprolite derived colluvium/alluvium	Lower

§ Newly proposed series in this study (see below). † UYT = Typic Yellow Ultic Soils, UYM = Mottled Yellow Ultic Soils, ROA = Acidic Orthic Recent Soils, ROM = Mottled Orthic Recent Soils, UPT = Typic Perch-gley Ultic Soils, GOJ = Argillic Orthic Gley Soils, RFMA = Mottled-acidic Fluvial Recent Soils, WF = Fluvial Raw Soils, WGT = Typic Gley Raw Soils, WGF = Fluid Gley Raw Soils. ‡ WD = well drained, MWD = moderately well drained, ID = imperfectly drained, SPD = somewhat poorly drained (newly proposed class in this study), PD = poorly drained, VPD = very poorly drained. [1] The information presented represents the redefinition or reinterpretation, by this study (below and in Chapter 4), of the information sourced primarily from Sutherland *et al.* (1980) and the associated unit-sheet descriptions. [2] The above soils were classified according to the NZSC by Clayden *et al.* (1997) and most of these classifications were confirmed in this study (Chapter 4, section 4.3.1.1). NZSC classes found by this study to differ slightly from those of Clayden *et al.* (1997) are indicated by an asterisk. [3] Based on soil morphology, soil chemical properties (% base saturation), and presumed vegetation cover (Sutherland *et al.*, 1980; Rijkse, 1996). [4] The terms used here to describe landscape position are formally defined and described in Chapter 4 (section 4.3.2).

3.4.1.1 Warkworth series

Two soil types of the Warkworth series were recognised in the vicinity of the study site: Warkworth clay loam and Warkworth clay loam hill soils. The reference site for the Warkworth clay loam is located on State Highway 1, opposite the intersection with McKinney Road, about 1 km south of Warkworth. The Warkworth hill soils reference site is located about 4 km north of Huapai on Waikoukou Road (Sutherland *et al.*, 1980).

Warkworth soils are formed from reddish or yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group). It was thought that some Warkworth clay loam soils formed from the "strongly weathered red volcanic grits" (presumably Parnell Grit beds) contained within the Pakiri Formation (Sutherland *et al.*, 1980). However, the soils formed on the andesitic Parnell Grit materials are likely to have properties more consistent with the concept of the Dome Valley series (Granular Soils of the NZSC). Therefore, soils formed from Parnell Grit material ought not to be included within the Warkworth series. The indigenous vegetation under which the Warkworth soils were formed probably consisted of kauri-podocarp forest with some patches of broadleaf species (c.f. Whangaripo, Puhoi, and Kara series). The Warkworth clay loam was reported as occupying rolling to gently rolling land whereas the Warkworth hill soils were thought to occur on strongly rolling to moderately steep short slopes (Sutherland *et al.*, 1980). In this study, the (redefined) Warkworth soils were found to occur predominantly on landforms within the more elevated upper part (zone) and the high or divergent middle parts of the landscape (e.g. shoulder slopes, upper back-slopes, and divergent middle back-slopes) (Chapter 4, sections 4.3.2 and 4.3.3).

The Warkworth clay loam and the Warkworth hill soils both have yellowish-brown subsoils and a horizon comprising more than 2% mottles (redox segregations) occurring within 30 cm of the soil surface. Despite both soil types having a mottled horizon near to the surface, they were described as well to moderately well drained (Sutherland *et al.*, 1980). According to the soil drainage classification in use today (Milne *et al.*, 1995), these soils would be designated as imperfectly drained. However, it appears that the concept of the Warkworth series was intended to encapsulate those yellowish-brown clayey soils, developed on strongly weathered Pakiri Formation materials, which have been strongly leached and which are relatively well drained (i.e. well to moderately well drainage classes) in comparison with other soils in the area (Rijkse, 1996).

The Warkworth soils were classified according to the New Zealand Genetic Soil Classification (NZGSC) (Taylor and Pohlen, 1962) as strongly leached to weakly podzolised (Northern) Yellow-brown earths (Sutherland *et al.*, 1980). The soils were reclassified using the NZSC as Typic Yellow Ultic (UYT) Soils (Clayden *et al.*, 1997). However, the latter classification is technically incorrect because the soil profiles represented in the unit-sheets were imperfectly drained rather than well or moderately well drained. According to the descriptions given in the unit-sheets, the Warkworth clay loam and Warkworth hill soils ought to be classified as Mottled Yellow Ultic (UYM) Soils. However, given that the Warkworth series was intended to encompass well to moderately well drained soils, the UYT classification ultimately is more appropriate.

3.4.1.2 Whangaripo series

In the Mahurangi area, the Whangaripo series is represented by four soil types, Whangaripo clay, Whangaripo clay hill soils, Whangaripo clay loam, and Whangaripo clay loam hill soils. However, a unit-sheet exists only for the Whangaripo clay. The reference-site for the Whangaripo clay is located about 1 km along Goatley Road, off State Highway 1, 2.5 km northwest of Warkworth (N.Z. Soil Bureau, 1968; Sutherland *et al.*, 1980).

The Whangaripo clay has formed from reddish or yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group), producing soils with yellowish-brown subsoils. Whangaripo clay soils were thought to have formed under broadleaf-podocarp forest with only some patches of kauri (c.f. Warkworth, Puhoi, and Kara series). These soils were reported to occupy rolling land and some strongly rolling short slopes (Sutherland *et al.*, 1980). In this study, the (redefined) Whangaripo soils were found to occur mainly on landforms within the upper and middle parts (zones) of the landscape (e.g. ridge summits, upper back-slopes, and middle back-slopes). Within the middle part of the landscape, the Whangaripo soils tend to favour the high or divergent slope positions but were also predominate on the convergent middle back-slopes of some sub-catchments (Chapter 4, sections 4.3.2 and 4.3.3).

The Whangaripo clay was described as having 10-12% redox segregations within 30 cm of the soil surface and was correctly deemed imperfectly drained (Sutherland *et al.*, 1980). Without a unit-sheet, the exact nature of the Whangaripo clay loam cannot be known except that the intention was for it to be well to moderately well drained (Sutherland *et al.*, 1980). It is likely to have properties very similar to those of the Warkworth series, but presumably was thought to be less leached.

Whangaripo clay soils were classified according to the NZGSC as moderately to strongly leached (Northern) Yellow-brown earths (Sutherland *et al.*, 1980) and were reclassified according to the NZSC as Mottled Yellow Ultic (UYM) Soils (Clayden *et al.*, 1997). The concept of the Whangaripo series was intended to encompass the moderately to strongly leached yellowish-brown clayey soils developed on strongly weathered Pakiri Formation materials that are moderately well drained to imperfectly drained. However, given the UYM classification of the Whangaripo soils, it is appropriate to restrict this series to the imperfectly drained soils whereas the well to moderately well drained (UYT) soils were better incorporated into the Warkworth series.

3.4.1.3 Puhoi series

Sutherland *et al.* (1980) subdivided the Puhoi series into four soil types: Puhoi clay loam, Puhoi clay loam hill soils, Puhoi light brown clay loam, and Puhoi light brown clay loam hill soils. The reference site for the Puhoi clay loam is located on Waiwera Hill, about 2.5 km north of Waiwera on State Highway 1 (N.Z. Soil Bureau, 1968; Sutherland *et al.*, 1980).

The Puhoi clay loam is formed from predominantly yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group). The native vegetation under which the soil has evolved was described as broadleaf forest with some podocarp and the occasional kauri tree (c.f. Warkworth, Whangaripo, and Kara series). The Puhoi clay loam was reported to occur on moderately steep, short and long slopes and some rolling ridges (Sutherland *et al.*, 1980). In this study, the (redefined) Puhoi soils were found occur to most commonly on landforms within the less elevated lower part (zone) and the low or convergent middle parts of the landscape (e.g. lower back-slopes, foot-slopes, and convergent middle back-slopes) (Chapter 4, sections 4.3.2 and 4.3.3).

The drainage is described as poor, which based on the unit-sheet, seems plausible. However, it is difficult to be sure because the range of matrix colours given in the unit-sheet description spans the low-chroma threshold (e.g. a matrix colour of 2.5Y 6/4-6/2 was assigned to a Bg horizon) (Sutherland *et al.*, 1980). Therefore, these soils are reinterpreted as being intergrades between the imperfectly and poorly drained soils (as currently defined).

The Puhoi clay loam soils were classified according to the NZGSC as weakly to moderately leached (Northern) Yellow-brown earths (Sutherland *et al.*, 1980) and were reclassified according to the NZSC as Mottled Yellow Ultic (UYM) Soils (Clayden *et al.*, 1997). If, in fact, the soil is poorly drained then it cannot be a UYM Soil, but would instead be a Gley Soil. Based on the unit-sheet description, the Puhoi soils are probably taxonomically more similar to the more-imperfectly drained Whangaripo clays than they are to the Gley Soils. Therefore, the classification of UYM is appropriate. Furthermore, it appears that the concept of the Puhoi series was intended to encompass the weakly to moderately leached clayey soils that are formed on strongly weathered Pakiri Formation materials and are at the threshold between the imperfect and poor drainage classes (considered to be imperfectly drained according to the existing drainage criteria but are assigned to the newly proposed 'somewhat poorly drained' class defined in this study – Chapter 4, section 4.3.1.2).

3.4.1.4 Kara series

Two soil types of the Kara series were identified in the vicinity of the study site: Kara silt loam and Kara peaty silt loam. Both soil types were mapped as complexes within the study area. One of the reference sites for the Kara silt loam was situated about 200 m north of Tomarata School on Pakiri Block Road in the Rodney District (Sutherland *et al.*, 1980).

The parent material of the Kara series was described as alluvium derived from sedimentary rocks (and presumably the associated saprolite). However, colluvium derived from yellowish saprolite is probably also a common parent material of the Kara soils within southern Mahurangi Forest (Rijkse, 1996). Kara soils were thought to have developed under kauri forest (c.f. Warkworth, Whangaripo, and Puhoi series) but at the time of description were covered by scrub and rushes. The Kara series was associated either with flattish 'terrace' landforms or low-lying landforms in general (Sutherland *et al.*, 1980). There is some evidence in the unit-sheets to suggest that the flattish 'terraces' referred to may in fact be the bench-like features that occur within side-slopes and may be associated with mudslide features (section 3.3.4.1). This study has confirmed that the (redefined) Kara soils occur most commonly on landforms within the lower part (zone) of the landscape (e.g. gully-floors) and also on flattish benches in more elevated positions (e.g. mudslide feature benches) (Chapter 4, sections 4.3.2 and 4.3.3).

The unit-sheet descriptions for the Kara series indicate that the described profiles were dominated by reductimorphic (gley) horizons (Sutherland *et al.*, 1980). Consequently, the drainage of the Kara series was described as being poor to very poor. However, these soils were classified, according to the NZGSC, as (Northern) Podzols by Sutherland *et al.* (1980) but were reclassified as Acidic Orthic Gley (GOA) Soils by Clayden *et al.* (1997) according to the NZSC. Within the study area, Argillic Orthic Gley Soils (GOJ) were identified rather than GOA Soils (the profiles described in the study area contained argillic horizons). It appears that the Kara series was intended to represent what were thought to be podzolised gley soils formed on alluvial/colluvial material. However, the unit-sheet descriptions did not provide any solid evidence for podzolisation (podzolic or humic horizons). Furthermore, the Kara soils were found by Rijkse (1996) to be only weakly leached according to base saturation data. Therefore, based on a modern interpretation of the unit-sheet descriptions, the Kara soils are probably best classified as Gley Soils because all described profiles had reductimorphic horizons occurring within 30 cm of the soil surface.

3.4.1.5 Atuanui series

The parent materials of the Atuanui series are reddish or yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group). These soils were classified according to the NZGSC as weakly to moderately leached steepland Yellow-brown earths (Sutherland *et al.*, 1980) and were reclassified according to the NZSC as Acidic Orthic Recent (ROA) Soils (Clayden *et al.*, 1997). Rijkse (1996) also included Orthic Raw (WO) Soils within the Atuanui series. In this study, imperfectly and somewhat poorly drained Mottled Orthic Recent Soils (ROM) were identified, in addition to the well to moderately well drained ROA soils, on the steeper slopes. The Atuanui series originally included only the well to moderately well drained steepland Recent Soils (Sutherland *et al.*, 1980) and no acknowledgement was given to the possibility that some of those soils could be imperfectly (or even somewhat poorly) drained by either Sutherland *et al.* (1980), Rijkse (1996), or by Clayden *et al.* (1997). Therefore, the concept of the Atuanui series has been expanded in this study to include all steepland Orthic Recent Soils (well to somewhat poorly drained). The (redefined) Atuanui soils occur on relatively steep slopes within the upper and middle parts (zones) of the landscape. Within the middle parts, they tend to occur on either the high or convergent middle back-slopes (Chapter 4, sections 4.3.2 and 4.3.3).

3.4.1.6 Whakapara series

Two soil types of the Whakapara series were identified: Whakapara silt loam and Whakapara mottled clay loam. These soil types were differentiated on the basis of drainage class — the Whakapara silt loam was described as well to moderately well drained whereas the Whakapara mottled clay loam was described as imperfectly to very poorly drained. The Whakapara soils formed from alluvium derived from eroded saprolite and associated sedimentary rocks. Both soil types, classified as Recent soils according to the NZGSC, were reported to occur on alluvial flats and some wider gully-floors (Sutherland *et al.*, 1980). It was confirmed in this study that the (redefined) Whakapara soils occur on the gully-floors within the lower part (zone) of the landscape (Chapter 4, sections 4.3.2 and 4.3.3). Clayden *et al.* (1997) reclassified both the Whakapara silt loam and the Whakapara mottled clay loam as Mottled Fluvial Recent (RFM) Soils according to the NZSC. Clearly, there is some confusion regarding the drainage condition of both Whakapara soil types because a well to moderately well drained soil (Whakapara silt loam) should not be included within a mottled subgroup of the NZSC nor should a potentially poorly drained soil (Whakapara mottled clay loam). Somewhat poorly drained Mottled-acidic Fluvial Recent Soils (RFMA) and Fluvial Raw Soils (WF) were identified in the study area (rather than RFM Soils) and were correlated to the Whakapara series due to their fluvial origin. Therefore, the Whakapara series was effectively expanded to incorporate the RFMA and WF Soils.

3.4.1.7 Pohuehue series (proposed)

None of the soils series previously mapped in the vicinity of the study area (nor within Northland as a whole) adequately represent the profile characteristics of the poorly to very poorly drained Typic Perch-gley Ultic (UPT) Soils identified within the study area. Therefore, it is proposed that a new series, the 'Pohuehue' series, named after the Pohuehue Scenic Reserve which is adjacent to the study area, be established to represent the UPT Soils in the Mahurangi area. The Pohuehue series is defined on the basis of the key soil profile description of the UPT Soil (Profile 4, Appendix One) and the general description of these soils given in Chapter 4 (section 4.3.1). Pohuehue soils formed from predominantly yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group) and most commonly occur on landforms within the lower part (zone) of the landscape (e.g. lower back-slopes and foot slopes) and also on mudslide feature benches in more elevated positions (Chapter 4, sections 4.3.2 and 4.3.3). The Pohuehue soils are probably weakly leached due to their poor drainage and occurrence in low-lying landscape positions.

3.4.1.8 Hungry Creek series (proposed)

The 'Hungry Creek' series, named after Hungry Creek which flows through part of the study area, is proposed to represent the poorly to very poorly drained Typic Gley Raw (WGT) Soils and the Fluid Gley Raw (WGF) Soils that were found to occur within the study area. These soils were not encompassed by any of the existing series. A general description of the Gley Raw Soils is given in Chapter 4 (section 4.3.1). Hungry Creek soils are formed from recently deposited colluvium and alluvium which have been derived largely from the saprolite regolith. The colluvial and alluvial materials were deposited within the lower part (zone) of the landscape where they contribute to the upbuilding of the gully-floors. The Hungry Creek soils commonly occur on gully-floors but can also occur on some lower back-slopes (Chapter 4, sections 4.3.2 and 4.3.3). They are likely to be weakly leached due to a combination of their youthful parent materials, poor drainage, and low-lying position in the landscape.

3.4.2 Previously recognised soil-landscape relationships

The relationship of the soil series and NZSC subgroups (as defined prior to this study) to observable landscape features in Mahurangi Forest was first investigated by Rijkse (1996) who presented the relationships in the form of soil-landscape models.

In the first model (applicable only to the southern part of Mahurangi Forest), Rijkse (1996) related soil drainage classes to several geomorphic factors (land elements, degree of slope dissection, and slope shape). Presumably, degree of dissection was associated with slope steepness. Soil drainage class was used because the diversity of soil series was considered to be too low for the purposes of establishing clear soil-landscape relationships (Rijske, 1996). The moderately well and imperfectly drained soils were found to predominate on ridge summits with the imperfectly drained soils more likely to occur on wider summits (>30 m). Strongly dissected back-slopes were found to contain well and moderately well drained soils with the latter more prevalent on concave slopes. Moderately dissected back-slopes were dominated by moderately well and imperfectly drained soils whereas imperfectly and poorly drained soils were predominant on linear to concave weakly dissected back-slopes (some moderately well drained soils were found on convex weakly dissected back-slopes). With respect to the foot-slope/toe-slope land element, moderately well and imperfectly drained soils were associated with strong dissection, and imperfectly and poorly drained soils were associated with moderate and weak dissection. Poorly and imperfectly drained soils were found to occur on the gully-floors (Rijkse, 1996). In essence, it was found that more strongly dissected and convex slopes tended to have better drained soils. It was also found that the poorer drained soils were more prevalent on the foot-slopes/toe-slope and gully-floor land elements (Rijkse, 1996).

In a second soil-landscape model applicable across the entire forest, Rijkse (1996) related the subgroups of the NZSC to the same geomorphic factors used in the first model (listed above). UYT (Warkworth series) soils were found to predominate on ridge summits and weakly to moderately dissected back-slopes and foot-slopes/toe-slopes. The Orthic Recent Soils and Orthic Raw Soils of the Atuanui series were associated with the strongly dissected back-slopes and foot-slopes/toe-slopes. Within the strongly dissected back-slope land element, the Recent Soils tended to occur on convex slopes whereas the Raw Soils tended to occur on the concave slopes. GOA (Kara series) soils were predominant on the narrower (<30 m) linear to concave gully-floors whereas the RFM (Whakapara series) soils tended to form on the wider (>30 m) and more linear gully-floors. The UYM (Whangaripo and Puhoi series) soils were sub-dominant on the weakly dissected back-slopes and foot-slope/toe-slopes and in the narrow gully-floors (Rijkse, 1996).

3.5 Land use and forest management history

Land use and management activities (particularly forest management activities) have the potential to substantially influence the nature of the landscape and the soils that occur within it (Bidwell and Hole, 1965; Fanning and Fanning, 1989; Simard *et al.*, 2001; Palmer *et al.*, 2004). A brief outline of land use history is given before the forest management history and activities are described in more detail. The land use capability classification of southern Mahurangi Forest is also discussed.

3.5.1 Land use history

Maps of vegetation cover for ca. 1840 AD show the study area to be largely in native forest but adjacent areas immediately to the south, and low lying areas, were covered by *Leptospermum* (manuka) and *Pteridium* (bracken), a result of (pre-European) Polynesian deforestation (McKinnon *et al.*, 1997; Newnham *et al.*, 2004). European settlers had cleared most of the remaining native forest from the Mahurangi (Warkworth) area by the end of the 19th century, replacing the forest with pasture. Dairy farming was conducted on the gently sloping land whereas the steeper land (like that on which the study site is located) was used for sheep and beef grazing (Feeney, 1984). Phosphate fertiliser and lime were probably applied to the soils under pasture (Groenendijk *et al.*, 2002). Some evidence of the harvesting of native timbers (abandoned logs tied with snig-chains) and of the subsequent pastoral history (old fences and gate posts), can still be observed within the forest today. Land use within the study site is now *Pinus radiata*-dominated, exotic plantation forestry.

3.5.2 Forest management history

Mahurangi Forest was established during the 1970s when blocks of the steeper, less productive farmland surrounding Warkworth were purchased and the pasture replaced with *P. radiata* trees. In some areas, the farmland had reverted back to scrubland. Where the land was scrub-covered, a gravity roller was most likely used to crush the scrub prior to it being burnt to make way for the pine seedlings (S. Dyne, 7 August, 2001, personal communication). It is possible that the pre-harvested area (pre-harvested plot) intensively investigated in this study (Chapter 4) was treated in the above fashion. The soils within the forest had not received fertiliser inputs since the establishment of the forest (Groenendijk *et al.*, 2002).

Today, the majority of the first crop of trees (first rotation) have reached maturity and have been harvested. For the purposes of this study, the term forest harvesting is used to refer to all activities, from the preparation of the site for harvesting through to the post-harvesting activities applied to prepare the site for the next rotation, which may, either directly or indirectly, have affected the soils or soil properties. However, in the main, 'forest harvesting' refers to the process of felling trees and extracting their stems (Dykstra and Heinrich, 1996). In southern Mahurangi Forest, the clear-felling approach to forest harvesting was employed and, in the post-harvested area (post-harvested plot) intensively studied in this project (Chapter 4), was undertaken using hauler-based harvesting techniques (S. Dyne, 7 August, 2001, personal communication). Clear-felling involves the systematic felling of all individuals within a stand of trees of the same age during a particular harvesting operation. Thus, clear-felling is commonly used when harvesting plantation forests (Forest Industries Training, 2004). Hauler-based harvesting (also known as cable logging) works by dragging the logs (sometimes along the ground and sometimes suspended in the air) from where they were felled up to a landing area (usually in a more elevated part of the landscape) using a system of cables. The cables are pulled by a hauler which is a piece of machinery (often mobile) consisting of a tall spar and a winch (Forest Industries Training, 2004). The set-up of a hauler-based system is illustrated by Figure 3.4.

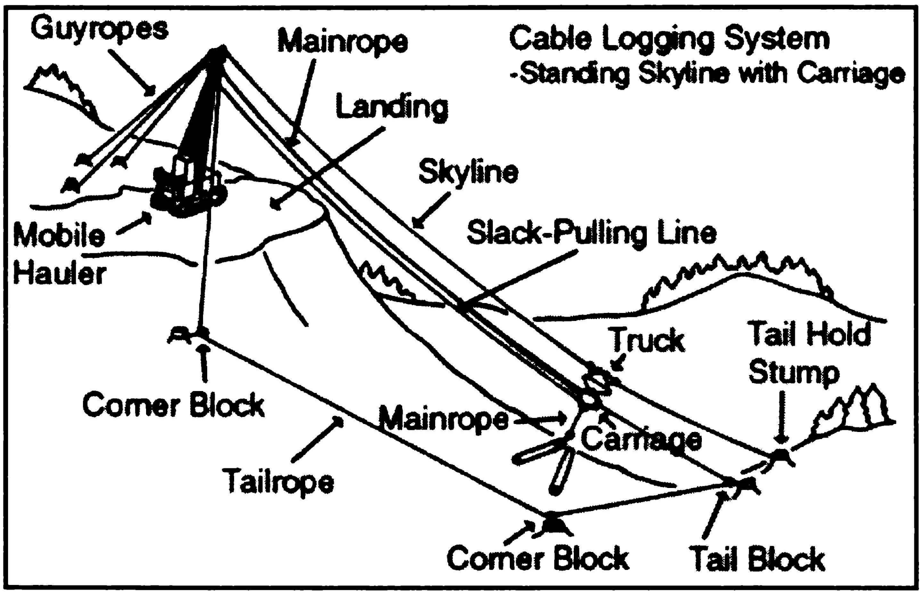

Figure 3.4. Diagram illustrating the set-up of a hauler-based harvesting (cable logging) system (Source: Forest Industries Training, 'Forestry insights' website, 2004).

Hauler-based harvesting was preferred over ground-based (skidder) harvesting in Mahurangi Forest because the slopes are relatively steep and the soils can be fairly wet throughout substantial proportions of the landscape for extended periods of time — skidders (tracked or rubber-tyred machines designed for dragging felled logs) are not well suited to use on steep slopes and may cause soil compaction if the soil is too wet (Forest Industries Training, 2004). However, some use was made of skidders/bulldozers and mechanised-harvesters for the harvesting of trees on the flatter and drier ridge summits in some areas.

Pre-harvesting activities included levelling summit hillocks adjacent to roads or at the ends of spur-ridge summits using earth-moving equipment. The purpose was to create landings for use during harvesting operations, both for stock-piling and loading logs. After harvesting, at least in the post-harvested plot intensively studied in this project, no fertiliser was added nor has it been since the land was converted from pasture (S. Anderson, 30 September, 2002, personal communication). Also, the slash (logs, branches, and foliage discarded during harvesting) was left across the post-harvested plot and some mounding of the soil had been performed on one of the ridge summits in order to ameliorate the soil compaction caused by heavy machinery (such as skidders or bulldozers) trafficking along the ridge. All harvested areas were replanted, after site-preparation, with a second rotation of *Pinus radiata* trees. Therefore, southern Mahurangi Forest is currently a mixture of mature first-rotation trees and juvenile second rotation trees of varying ages (i.e. the harvesting was staggered).

3.5.3 Land use capability classification

The majority of the study site would fall within either the VIe1 or VIe8 Land Use Capability (LUC) units defined by Harmsworth (1996). LUC class VI land is considered to be non-arable and is suited to either pastoral or plantation forestry uses. The LUC subclass (VIe) indicates that the main limitation of the land is its potential erodibility. The VIe1 and VIe8 units were differentiated mainly on the basis of slope steepness: the slopes of the VIe1 unit were predominantly strongly rolling to moderately steep (16-25°) whereas those of the VIe8 unit were mainly moderately steep to steep (21-35°) (Harmsworth, 1996). Forestry site index, a measure of site productivity, was assigned to each LUC unit in the region. The site index, defined as the average height (m) of 20 year-old *P. radiata* trees of the VIe1 and VIe8 units, is 31-34 m (Harmsworth, 1996). Rijkse (1996) indicated that tree growth in Mahurangi Forest may be limited either by soil erosion (related to slope steepness), poor soil drainage (in some parts of the landscape), or the generally low soil nutrient levels.

3.6 Summary

Southern Mahurangi Forest is a first and second rotation, *P. radiata*-dominated, exotic plantation forest situated just south of Warkworth, northern Auckland, New Zealand. The soils of the forest were formed from clay-rich saprolite, or reworked saprolite materials, derived largely from the volcanic-rich sandstones and siltstones of the Pakiri Formation (Waitemata Group). Very thin, distal tephras and probably aeolian dust are additional but relatively minor components of the soil-landscape. Soil formation occurred within a stream-incised, strongly rolling to very steep, hill country land system, under (during the Present Interglacial) broadleaf-conifer forest and a relatively warm and generally moist but occasionally droughty climate with very high solar radiation. During glacial periods the landscape remained largely forested but it was beech-dominated and conditions were cooler and substantially drier.

The most common, previously mapped, soil series in the area are part of the Puhoi suite and were generally ill-defined according to modern soil description and classification systems. Differences in the soils are related mainly to profile drainage, topographic position, and degree of profile development. Soil drainage classes and subgroups of the NZSC have been found to be related to geomorphic factors such as land elements, degree of slope dissection, and slope shape. Mudslides are the dominant form of mass-movement within the study site (and surrounding region) and appear to have had a major impact on the topography and pedology of the forest. Pastoral farming replaced the native vegetation and in turn has been replaced by exotic plantation forestry. The study site is classified as non-arable land with the limitation of potential erodibility (LUC unit: VIe). The main forest management activity applied within the study site is hauler-based, clear-fell, forest harvesting.

3.7 References

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CHAPTER FOUR

Spatial prediction of soil drainage classes: impacts of forest harvesting on qualitative soil-landscape modelling

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4.1 Introduction

The movement of New Zealand's forestry industry towards sustainable and site-specific forest management has created new and specific demands for forest soil information. Accurate information regarding the spatial distribution of locally significant soil classes (e.g. drainage classes), in addition to detailed information on the magnitude and variability of certain target soil properties, is required for assessing and monitoring forest site quality and for implementing site-specific forest management programmes (Payn and Thwaites, 1998; Turner *et al.*, 1999; Payn *et al.*, 1999, 2000; Fox, 2000; Shaw and Carter, 2002). There is also a commercial desire for this soil information to be collected in a cost-effective manner and presented in easily accessible, flexible formats (Payn and Thwaites, 1998).

Most existing soil class information relating to New Zealand's forest estates is inadequate, being general purpose soil classes mapped at scales typically too coarse for the comprehensive assessment of forest site quality and the implementation of site-specific forest management (Jones, 1998; Payn and Thwaites, 1998; Payn *et al.*, 1999, 2000). Therefore, the required soil class information must be collected before sustainable and site-specific forest management can be achieved (Payn *et al.*, 1999).

Although it is now widely recognised that conventional soil survey is unable to adequately provide the required detailed soil information (McKenzie and Austin, 1993; Moore *et al.*, 1993; Payn and Thwaites, 1998; Thwaites and Slater, 2000), the most suitable approach to predicting and mapping the spatial distribution of soil classes in plantation forest environments has not yet been clearly established. However, qualitative soil-landscape modelling has been highlighted as a potentially useful tool for this purpose (Jones, 1998; Hill, 1999). When used in association with spatial information technology (e.g. GIS), qualitative soil-landscape modelling has the potential to provide the required soil class information in appropriate formats (e.g. McLeod *et al.*, 1995; Rahman *et al.*, 1997). Furthermore, the qualitative soil-landscape modelling approach may be cost effective because it predicts soil class distribution from readily available and relatively cheap ancillary (explanatory) landscape information (Hewitt, 1993).

The qualitative soil-landscape modelling approach to the spatial prediction of soil classes, widely adopted within New Zealand (e.g. McIntosh, 1994; McLeod *et al.*, 1995; Hewitt, 1995; Webb and Burgham, 1997), has generally been found to perform well in agricultural and range-land environments (e.g. McLeod *et al.*, 1995; Rijkse and Trangmar, 1995) and its potential usefulness within plantation forest environments has been recognised (Jones, 1998; Hill, 1999; Hill *et al.*, 2000). However, the suitability of qualitative soil-landscape modelling to plantation forest environments has not yet been comprehensively evaluated. Forest land-management activities such as clear-fell harvesting can cause considerable soil disturbance (Simard *et al.*, 2001; Palmer *et al.*, 2004) and have been shown to significantly alter soil properties in both New Zealand (e.g. Parfitt *et al.*, 2002) and elsewhere (e.g. Simard *et al.*, 2001). Therefore, the soil-landscape relationships used by qualitative soil-landscape models to predict spatial patterns of soil class distribution may be altered or weakened by forest harvesting (Block *et al.*, 2002) which, in turn, may reduce the predictive performance of qualitative soil-landscape models. However, the impacts of forest harvesting on soil-landscape relationships and the predictive performance of qualitative soil-landscape modelling had not been investigated. Gaining an understanding of the impacts of forest harvesting on the predictive performance of qualitative soil-landscape models is therefore a crucial step towards the comprehensive evaluation of their suitability to plantation forest environments.

This chapter reports on a study conducted as part of a wider investigation into the impacts of hauler-based, clear-fell, forest harvesting on the performance of soil-landscape modelling as a tool for the spatial prediction of soil classes and target soil properties in a radiata pine forest. The research was conducted within southern Mahurangi Forest, an exotic, *Pinus radiata*-dominated plantation forest, situated on the Northland Peninsula, North Island, New Zealand. The objectives of this study were to determine the impacts of hauler-based, clear-fell, forest harvesting on (a) the relationships between locally significant soil classes and landscape units and (b) the performance of the qualitative soil-landscape modelling approach to the spatial prediction of locally significant soil classes.

4.2 Methodology

In this study, the soil-landscape models were developed primarily for the purpose of evaluating the impacts of forest harvesting on the predictive performance of qualitative soil-landscape models. Therefore, the methods used to develop and validate the models differ somewhat from those normally used to develop and validate soil-landscape models for the sole purpose of mapping soils across large areas. However, the development of the landscape frameworks in this study and their use in the development and application of the soil-landscape models was in general accordance with the land systems approach (defined in section 4.3.2.1), as described by Lynn and Basher (1994).

In addition to describing the methods of soil-landscape model development, application, validation, and representation, this section outlines the scoping study conducted to guide the development of the wider study. The establishment of the intensive sampling plots and the observation of geomorphic factors and soil morphology within the plots are also described. The Geographic Information System ARCGIS 8.2 (ESRI, 2002) was used to develop and present all maps throughout the chapter. The contour data and other topographic coverages used in generating the maps were provided by Carter Holt Harvey Forests Ltd. Although relevant to this chapter, the methods of terrain analysis and terrain attribute derivation were more appropriately placed in Chapter 5, section 5.2.3. Note that the terms 'sample point' and 'data point' used below refer to the same points in space: 'sample point' is used when describing the collection of data whereas the term 'data point' is used when discussing the subsequent analysis or interpretation of the data. A comprehensive description of the study site location and environment was given in Chapter 3.

4.2.1 Scoping study

A scoping study was undertaken prior to developing the qualitative soil-landscape models in order to confirm the presence of the range of soils previously identified in the study area (Chapter 3, section 3.4), clarify their classification, and further explore their general relationships to the landscape. The soils and landforms were observed briefly in road cuttings throughout the land system during field reconnaissance. However, the majority of more detailed observations were made within one particular part of the land system (i.e. a training window). The training window was carefully selected to ensure that a representative range of soils and landforms were encapsulated. The selection was made using field reconnaissance and contour map interpretation.

The landforms contained within the training window were identified and described in the field using adaptations of the geomorphic descriptors given in Milne *et al.* (1995). Soil observations (auger observations and profile descriptions) were made within the training window using previous experience to select critical sites. Detailed soil profile descriptions were conducted by digging pits or refreshing road cuts and erosion scarp faces. The locations of the profile descriptions within the training window and the location of the training window itself (inset) are shown in Figure 4.1. The profiles were described using the standard methodology and horizon nomenclature for New Zealand soils (Clayden and Hewitt 1994; Milne *et al.* 1995). The brief auger observations, made across the training window, provided additional information regarding the soil-landscape relationships. Only key soil profile descriptions are included in the thesis (Appendix One).

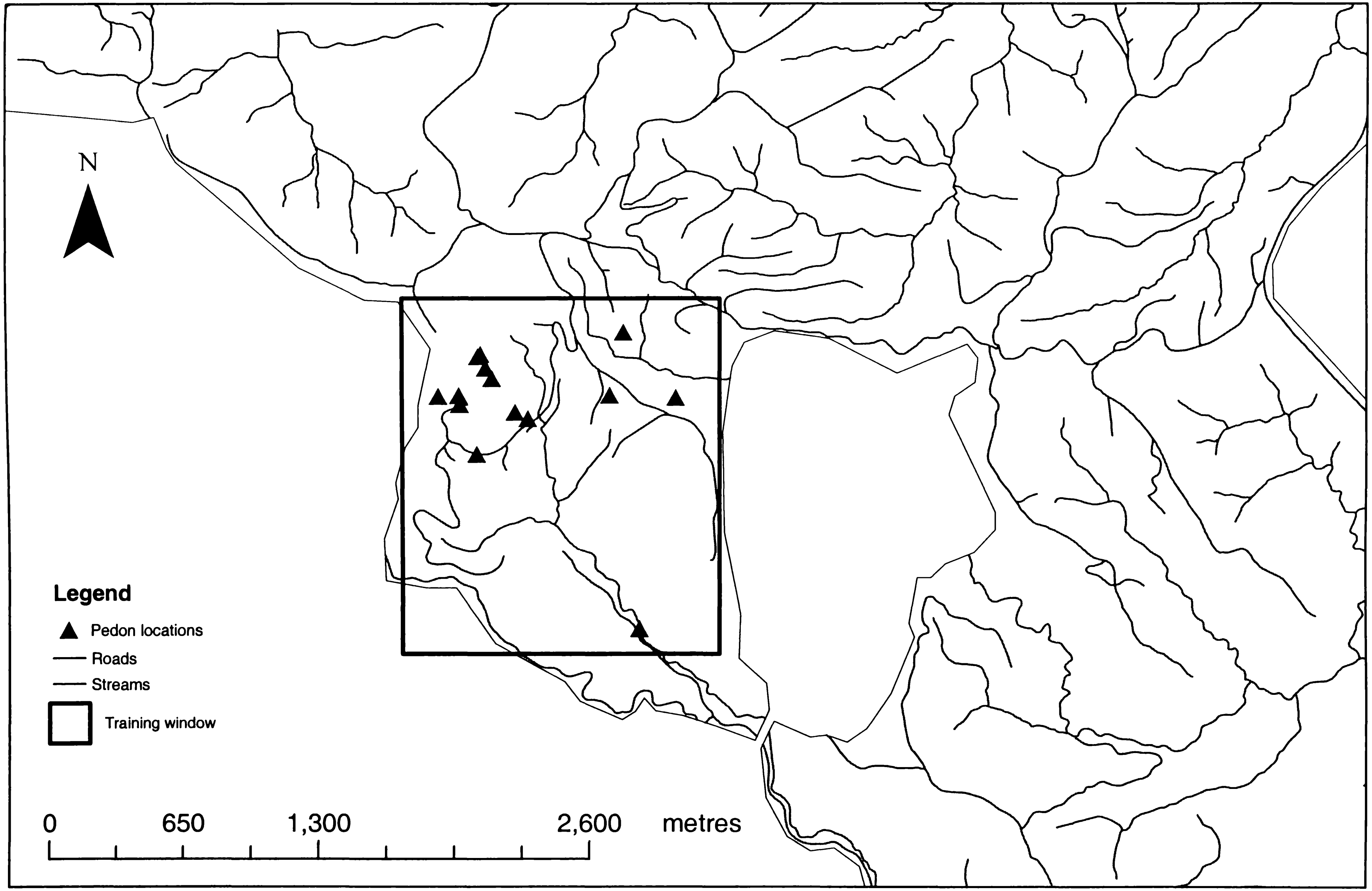


Figure 4.1. Map showing the locations of the profile descriptions within the training window.

Samples were taken from each horizon in all profiles for the laboratory measurement of some key soil properties for the purposes of soil classification (e.g. soil pH and particle size distribution). Subsoil pH was measured in all profiles whereas particle size was determined only for selected horizons in some profiles. Soil pH was measured in H_20 (using a 1:2.5 soil to distilled water ratio) according to the method of Blakemore *et al.* (1987) and particle size was determined using the pipette method as described by Claydon (1989). The particle size and pH data are presented in Appendix One as a part of the key profile descriptions.

The data obtained from the profile descriptions and the laboratory analyses allowed for the profiles to be classified to the soilform level of the New Zealand Soil Classification System (NZSC) (Clayden and Webb, 1994; Hewitt, 1998) and to the subgroup level of Soil Taxonomy (Soil Survey Staff, 1999). The profiles were also classified in terms of their drainage condition (degree of wetness) using the New Zealand soil drainage classification (Milne *et al.*, 1995).

The results of the scoping study were presented as a conference paper (Jones *et al.*, 2000). The key profile descriptions are reproduced in this thesis but the results relating to the soil-landscape relationships have been largely superseded by new and more comprehensive data and so are not reproduced here. However, it is important to note that the scoping study highlighted four key points: (1) soil differences were mainly related to drainage condition, (2) some imperfectly drained soils were clearly 'wetter' than others (two morphologically distinct profile types were identified), (3) soil drainage condition appeared to be largely controlled by geomorphic factors, and (4) saprolite type had some relationship to soil drainage. The recognition of these points resulted in several critical steps being taken with respect to the further development of the study. Firstly, the soil drainage criteria and classes of Milne *et al.* (1995) were modified for the purposes of this study (section 4.2.4.2 and Chapter 5) and the resulting modified soil drainage classes (section 4.3.1.2) were identified as the locally significant soil classes and chosen (ahead of the subgroups of the NZSC) to be the primary classes of the qualitative soil-landscape models. Secondly, the initial landscape framework developed during the scoping study was modified (sections 4.2.4.3 and 4.3.2.1) to emphasise the geomorphic factors potentially relevant to water movement in order to better partition the variation in soil drainage conditions. Thirdly, the effect of saprolite type on soil drainage was investigated. Saprolite type was found to have no effect on soil drainage or distribution (in fact, the reverse was found: saprolite type is affected by soil drainage) (Jones *et al.*, 2002). Therefore, saprolite type had no predictive value and so was not factored into the soil-landscape models. The results of the saprolite study are to be published independently of the thesis.

4.2.2 Plot establishment

A rectangular area of approximately 240 ha, separate from that used for the scoping study, was selected to accommodate the development and validation of the soil-landscape models (among other prediction techniques — Chapter 6). The selected area will be referred to as the Predictive Modelling Experimental Area (PMEA). Two separate but essentially adjacent sampling plots, one in a pre-harvested area, the other in a post-harvested area, were established within the PMEA and a separate qualitative soil-landscape model was developed and validated within each plot.

Separate plots were used to determine the impacts of forest harvesting, rather than a single plot sampled prior to and then after harvesting, because it was anticipated that the soils and soil properties would probably be in a state of flux in the first year or so after harvesting in response to the change in vegetation cover and the associated disturbance of the soil (Parfitt *et al.*, 2002). That is, the soil property values in a recently harvested area were not expected to be representative of the values in areas that had been harvested several years ago. It was decided that the most realistic and meaningful assessment of the impacts of forest harvesting would be achieved by sampling an area (near to the pre-harvested area) that had been harvested about two years prior to sampling because it would be more likely to be in equilibrium with its new environmental conditions. A full description of the plots and the methods used in their establishment is given below.

The sampling plots were approximately 5 ha (~200 m × ~250 m) in size and each consisted of 208 sample points on a 16.7-m regular grid pattern. A regular grid sampling design was adopted because it allowed for the comparison of a range of prediction techniques. This type of approach has commonly been used in similar studies (e.g. Moore *et al.*, 1993; Odeh *et al.*, 1994, 1995; Chaplot *et al.*, 2000). One plot was under first rotation mature *Pinus radiata* trees, i.e. the pre-harvested plot; the other plot had been harvested and was under second rotation, two-year-old trees, i.e. the post-harvested plot. The pre-harvested plot was effectively the control plot and hauler-based, clear-fell, forest harvesting was the treatment applied to the post-harvested plot. The plots, each encompassing a small sub-catchment, were situated approximately 350 m apart on either side of a main ridge, the pre-harvested plot predominantly east facing and the post-harvested plot predominantly west facing (Figure 4.2).

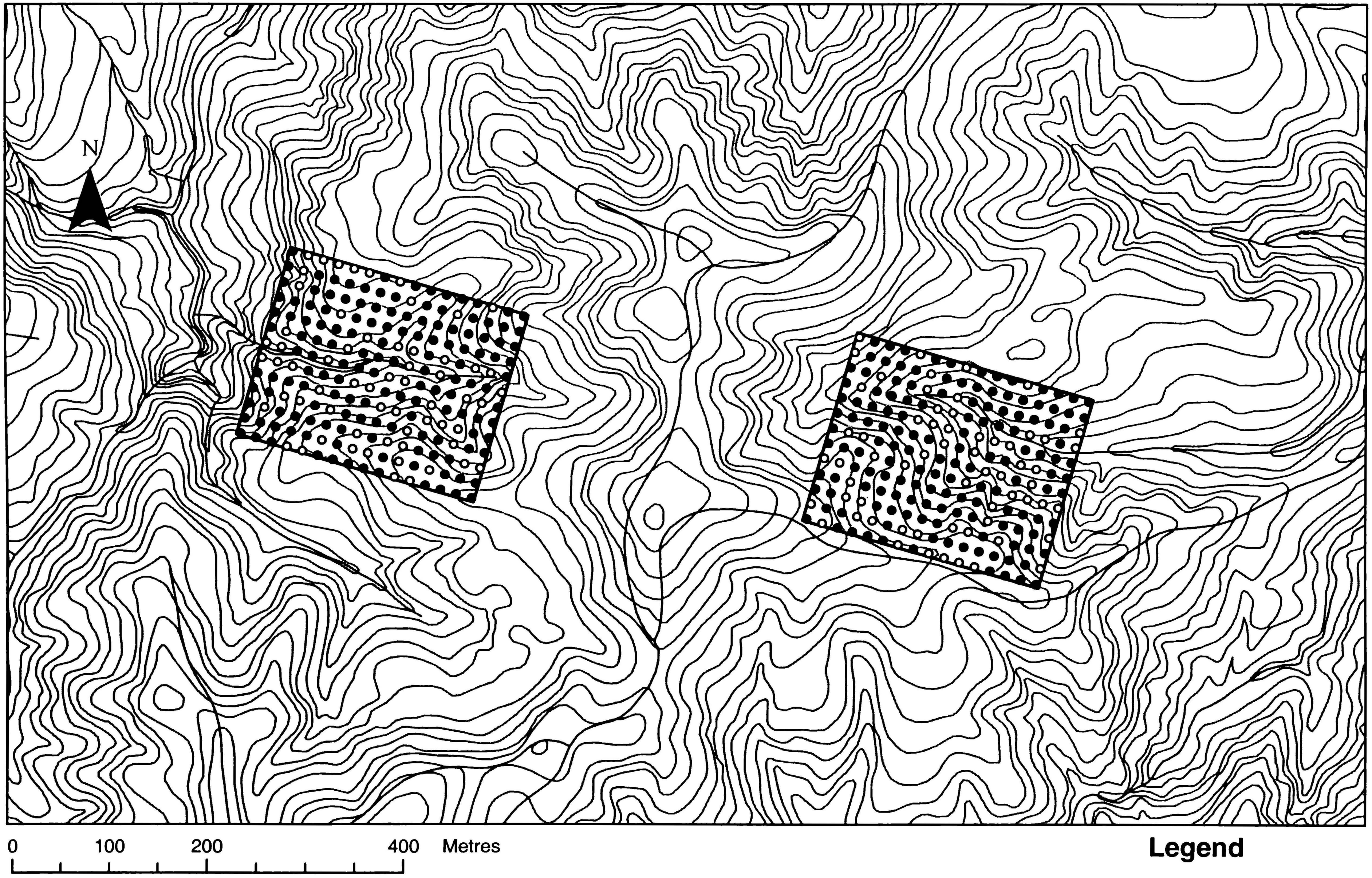


Figure 4.2. Map showing the relative position of the pre-and post-harvested plots within the PMEA.

The plots were marked-out in the field from predetermined starting points and plot boundaries – accurately drawn on a contour map – using a compass and tape measure. Marker pegs were placed in the ground every 16.7 m along the predetermined bearing to indicate the location of each sample point. Before each marker peg was fixed a compass bearing was taken in the reverse direction to ensure the peg was correctly located.

The co-ordinates (NZ map grid) of the starting points of each plot were determined from the 5-m contour map in ARCGIS (ARCMAP). The starting point co-ordinates were recorded and used in a MICROSOFT EXCEL (Microsoft Corporation, 2002) spreadsheet to calculate the co-ordinates of all other sample points by employing basic trigonometry. It was assumed that the position of the sample points in the field followed the intended regular grid pattern exactly. It was necessary to make this assumption because the decision was made not to use global positioning system (GPS) technology to determine the sample point co-ordinates. A GPS could not determine the sample point co-ordinates in the pre-harvested plot as accurately as those in the post-harvested plot because the closed canopy of the pine trees in the pre-harvested plot would interfere with the satellite signals (Firth and Brownlie, 1998). More accurately located sample points in the post-harvested plot may have introduced bias into the comparison of prediction techniques between the two plots. However, the assumption that the sample points conformed exactly to a regular grid does not entirely hold true because the predetermined sample spacing was measured over an irregularly sloping land surface (rather than a flat surface) meaning that, in plan view, the sample spacing was not perfectly regular. Therefore, a correction was applied to the regular grids of both plots to account for the resulting reduction in sample spacing in the plan view. The sample spacing was systematically reduced by 0.5 m (estimated on the basis of an average slope steepness of 15°) in both the northing and the easting directions from the starting point. Points known to be located next to the streams in each plot were used as reference points to corroborate the correction. The same correction was applied to both plots.

The accuracy of the estimated sample points was assessed by comparison with 28 GPS readings made at selected sample points in the post-harvested plot using a GARMIN ETREX hand-held GPS. On average there was a 5-m difference in the northing values and a 6-m difference in the easting values. Given the scale of variation in landforms within the plots, this error was not considered excessive and a visual comparison of the GPS and estimated sample points in ARCMAP confirmed that the applied correction was appropriate.

4.2.3 Field observation of soils and landforms

4.2.3.1 Observation of soil morphology

Auger observations to a depth of approximately 1.2 m were made at each sample point in both plots in order to describe the soil morphology. At each sample point the auger hole was made at about 0.5 m distance from the marker peg in any direction, placing it within the area defined to constitute an individual soil sample point (Chapter 5, section 5.2.1.4). Some key elements of the soil morphology were briefly described and recorded in order to classify the soil at each point into NZSC subgroups (Hewitt, 1998) and into modified soil drainage classes. The key morphological elements described were (1) depth to horizon boundaries, (2) matrix colour, (3) presence of redox mottles (redox segregations), (4) presence of reduced mottles (redox depletions), (5) horizonation, (6) solum thickness, and (7) saprolite type (differentiated by colour). The brief description of the auger samples was performed (as far as was practicable) in accordance with the standard soil description methodology (Clayden and Hewitt, 1994; Milne *et al.*, 1995).

4.2.3.2 Observation of geomorphic factors

Concurrent with the auger observations, several geomorphic factors were also visually described and recorded at each sample point. The geomorphic factors described were (1) land element or sub-element of the initial landscape framework (e.g. wide ridge summit slope), (2) relative landscape position (e.g. lower back-slope), and (3) profile and contour slope-shape (e.g. convex/concave). The geomorphic descriptions were made using an adaptation of the geomorphic descriptors given in Hall and Olson (1991) and Milne *et al.* (1995).

4.2.4 Model development

The process used in developing both soil-landscape models had five main steps: (1) selection of the development and validation data sets for each plot, (2) modification of the soil drainage classes, (3) refinement of the landscape framework and definition of the landscape units, (4) formulation, description, and interpretation of the soil-landscape relationships, and (5) formalisation of the soil-landscape relationships and definition of the soil-landscape units. These steps are outlined or described below. All analyses of soil-landscape relationships were performed using MICROSOFT EXCEL.

4.2.4.1 Selection of development and validation data sets

Within each plot, the soil-landscape models were developed using only a proportion (approximately 70%) of the total number of data points — the development set. A development set, consisting of 146 randomly selected data points, was established for each plot. The procedure for randomly selecting a development set was performed on each plot separately. Therefore, the data point identification numbers of the development set in the pre-harvested plot are different from those in the post-harvested plot. The development sets were selected by generating a set of random numbers, one for each of the 208 data points in a plot. The data points were then ranked according to their corresponding random numbers (from the largest random number to the smallest). The first 146 data points on the resulting list were assigned to the development set. The remaining 62 data points were assigned to the validation set (section 4.2.5) and were not used for model development.

4.2.4.2 Modification of the soil drainage classes

The soil drainage classes presently used in New Zealand, and the criteria used to define them (Milne *et al.*, 1995), were modified to better express the variation in soil drainage conditions found to occur in the forest. Four modified drainage classes were defined (1) 'Well Drained', (2) 'Imperfectly Drained', (3) 'Somewhat Poorly Drained', and (4) 'Poorly Drained'. The well drained and moderately well drained classes of the existing criteria were simply amalgamated (with some slight modification to the existing criteria) and called 'Well Drained'. Likewise, the poorly drained and very poorly drained classes were amalgamated and termed 'Poorly Drained'. For the purposes of this study there was no practical value in making the distinction between well and moderately well drained soils or between poorly and very poorly drained soils. The most substantial modification was the separation of the existing imperfectly drained class into two classes: Imperfectly Drained and Somewhat Poorly Drained. The separation was made on the basis of a difference in profile morphology (hydromorphology) and was later found to be very important with respect to differences in the forest management-related target soil properties (Chapter 5, section 5.3.3). Some slight adjustments were also made to the wording used in the criteria for all classes. The modified soil drainage classes were chosen as the primary soil classes to be used in the development the soil-landscape models because they partition the variation in the soils of the forest more effectively than the NZSC subgroups (section 4.3.3.1). That is, they are locally significant soil classes. The modified soil drainage classes and their defining criteria are described in section 4.3.1.2.

4.2.4.3 Refinement of the landscape framework

The initial landscape framework was modified, refined, and simplified in a multi-step process. The landscape framework evolved by (1) subdividing the side-slope back-slope land element by relative landscape position into several 'sub-elements' (thus finalising the 'modified initial landscape framework' — section 4.3.2.1), (2) grouping the land elements and sub-elements of the modified initial landscape framework into several 'land zones', (3) classifying the various slope-shapes into slope-shape classes, (4) subdividing the Middle land zone into 'sub-zones' on the basis of slope-shape class, (5) classifying the relative elevation data into relative elevation classes, and (6) regrouping the sub-zones of the pre-harvested model into two new sub-zones on the basis of relative elevation class. The landscape units of each model were then defined.

Identical procedures were followed in the refinement of the landscape framework of each model. The grouping and subdivision of the geomorphic factors and relative elevation data (in steps 2-6 above) were made with reference to the modified soil drainage class data to ensure that the variation in soil drainage was partitioned effectively. The modified initial landscape framework and the refined landscape frameworks are presented and discussed in section 4.3.2.

Subdivision of the side-slope back-slope element by landscape position

At the outset of the refinement process it was decided that the side-slope back-slope land element (section 4.3.2.1) would be subdivided into several sub-elements on the basis of relative landscape position. The reasons for this were twofold. Firstly, the scoping study indicated that the relative landscape position was an important geomorphic factor to consider, and, secondly, the side-slope back-slope element was the only one that extended from upper landscape positions to lower (most others occupy either higher or lower positions). Upper, middle, and lower side-slope back-slope sub-elements were recognised. These landscape positions were assigned by estimating approximate relative slope position in the field.

Grouping the land elements and sub-elements into land zones

The relationships between the modified soil drainage classes and the land elements and sub-elements were examined by sorting the modified drainage class data by land element and sub-element. Clear, meaningful, and practically applicable soil-landscape relationships were not apparent because the fairly large number of large scale land elements and sub-elements resulted in a large amount of unnecessary detail and complexity, the data being spread too thinly, and the repetition of relationships (by similar or contiguous land elements and sub-elements). The land elements and sub-elements that contained a similar assemblage of modified drainage classes generally occurred in a similar position or 'zone' within the landscape. Therefore, the land elements and sub-elements were grouped into three land zones: (1) Upper, (2) Middle, and (3) Lower. These land zones essentially (but not exclusively) subdivide that landscape on the basis of broad landscape position (section 4.3.2.2). Grouping the land elements and sub-elements into land zones reduced the repetition of relationships and thus highlighted the main relationships more clearly.

Classification of slope-shapes

Several profile/contour slope-shape permutations were initially identified (e.g. concave/convex, concave/concave, or convex/concave) (Figure 4.3). The modified drainage class data were grouped by profile/contour shape so that the effect of slope-shape on soil drainage could be examined. Considerable repetition of relationships leading to unnecessary complexity was found with the initial profile/contour slope-shapes. Therefore, in order to simplify and clarify the information slope-shape provided, the various profile/contour slope-shape combinations were grouped into two more meaningful slope-shape classes: (1) Convergent slopes and (2) Divergent slopes. In general, predominantly concave slopes were assigned to the Convergent class whereas the predominantly convex slopes were assigned to the Divergent class. However, there were a couple of exceptions. In the pre-harvested plot, the linear/linear and concave/convex slopes were more appropriately placed within the Convergent class whereas in the post-harvested plot, they were best placed within the Divergent class. Also, the linear/concave slopes were most appropriately placed within the Divergent class for both plots even though the linear/concave shape would normally be considered to be convergent. The examination of modified drainage class sorted by slope-shape also revealed that profile shape was generally more important than contour shape in determining the drainage condition of the soil.

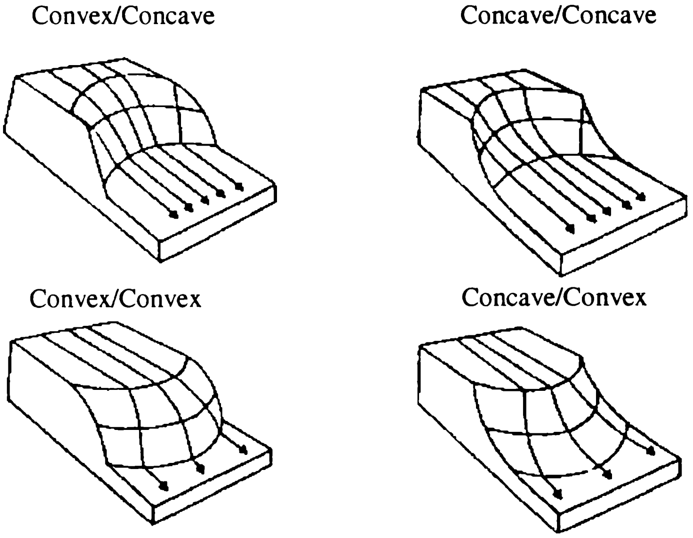


Figure 4.3. Slope-shape classes and expected flow directions (adapted from Huggett, 1975 after Hall and Olson, 1991, p. 13).

Subdivision of the Middle land zone by slope-shape class

The modified drainage class data were sorted by slope-shape class and then by land zone to determine whether the introduction of slope-shape class to the landscape framework would improve the partitioning of differences in soil drainage and, consequently, the representation of the soil-landscape relationships. There was no advantage found in subdividing the Upper or Lower land zones by slope-shape class (soil drainage classes were similar regardless of whether slopes were convergent or divergent) in either plot. However, some improvement, in the form of a clarification of relationships, was found when the Middle zone was subdivided into convergent and divergent parts. Thus two sub-zones were defined: Middle-Convergent (Middle-C) and Middle-Divergent (Middle-D). The improvement was slightly more pronounced in the post-harvested plot than in the pre-harvested plot.

Classification of the relative elevation data

The relationship of modified drainage class to the terrain attributes was investigated using box and whisker plots. Relative elevation (a measure of relative landscape position — Chapter 5 section 5.2.3.3) was found to be relatively strongly related to the modified drainage classes in the pre-harvested plot where it provided a useful description of the influence of relative landscape position on soil wetness (Figure 4.4). However, no clear relationships were observed between the modified drainage classes and the terrain attributes in the post-harvested plot. Therefore, the incorporation of the relative elevation data into the landscape framework was further pursued only for the pre-harvested plot.

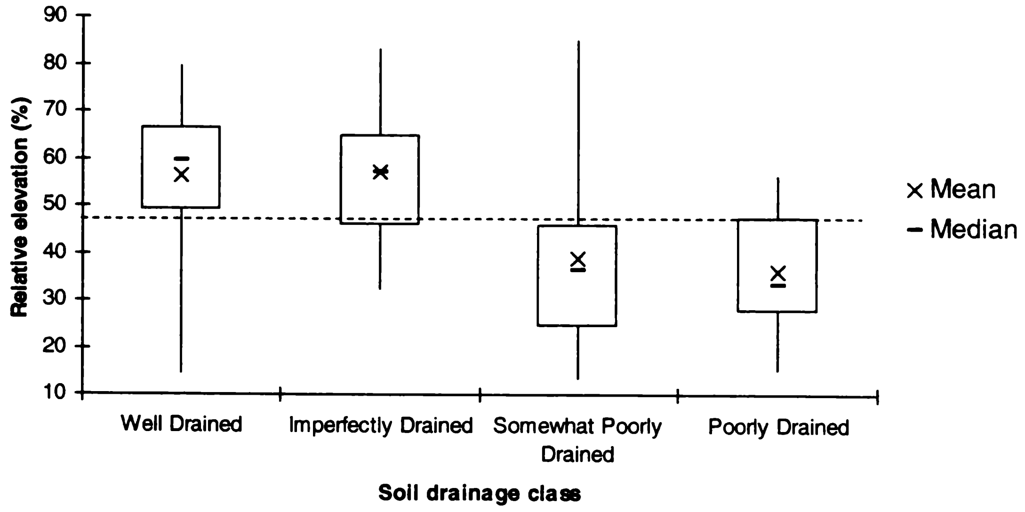


Figure 4.4. Relationship of the modified soil drainage classes to relative elevation in the pre-harvested plot. The dashed line represents the 47% relative elevation threshold.

A threshold relative elevation value was calculated to represent the observed separation of the modified drainage classes in the pre-harvested plot by taking the average of the lower quartile values of the Well and Imperfectly Drained soils (which occurred at higher relative elevations) and the upper quartile values of the Somewhat Poorly and Poorly Drained soils (which occurred at lower relative elevations). The threshold relative elevation value (calculated to be 47%) was used to classify the relative elevation data into two classes: High and Low. All data points of the pre-harvested plot with a relative elevation above the threshold were assigned to the High class whereas those parts with relative elevations equal to or below the threshold were assigned to the Low class.

Regrouping of the pre-harvested plot sub-zones by relative elevation class

The modified drainage class data of the pre-harvested plot were sorted by relative elevation class and then by land zone and sub-zone to determine whether the subdivision of the land zones and sub-zones by relative elevation class would explain more of the variation in soil drainage and thus strengthen the soil-landscape relationships. There was no advantage found in subdividing the Upper or Lower land zones by relative elevation class in either plot because these zones correspond almost exclusively to one relative elevation class or the other by definition. However, the subdivision of the Middle sub-zones did indicate that the incorporation of relative elevation class into the landscape framework of the pre-harvested model would improve the partitioning of the variation in soil drainage. Moreover, it was found that the Middle-C and Middle-D sub-zones had become redundant for two reasons. Firstly, the differences in soil drainage between the Middle-C and Middle-D sub-zones within a given relative elevation class were no longer evident. Secondly, the Middle-C and Middle-D sub-zones within the High relative elevation class contained a distinctly different assemblage of soil drainage classes to those in the Low relative elevation class (i.e. relative elevation class provided a better subdivision of the Middle zone than slope-shape class did in the pre-harvested plot). Therefore, the Middle-C and Middle-D sub-zones were dissolved and replaced by two new sub-zones based on relative elevation class: Middle-High (Middle-H) and Middle-Low (Middle-L).

Definition of the landscape units

On completion of the landscape framework refinement process, the landscape units — the functional units of the refined landscape framework — were defined (section 4.3.2.3). The landscape units (based on the zones and sub-zones) were then assigned to all data points (development and validation) using the geomorphic factor and relative elevation data collected at those points.

4.2.4.4 Formulation, description, and interpretation of soil-landscape relationships

The soil-landscape relationships were primarily formulated by sorting the modified drainage class data by landscape unit. The abundance of each drainage class occurring within each landscape unit was calculated (expressed as proportions of the total observations made within a given landscape unit) and plotted. The graphic representation of the soil-landscape relationships facilitated the description and interpretation of the relationships. The relationships between the landscape units and the NZSC subgroups were examined in order to provide further insight into, and a more in-depth understanding of, the detailed soil-landscape relationships not explicitly communicated by the functional soil-landscape models. The relationship of the land elements and sub-elements to the NZSC subgroups was included in this deeper analysis of soil-landscape relationships (section 4.3.3.1).

4.2.4.5 Formalisation of the soil-landscape relationships

The formalisation of the soil-landscape relationships occurred in two stages. Firstly, the modified soil drainage classes were amalgamated into two broad soil drainage classes; secondly, the broad drainage classes were used to assign the landscape units to one of two soil-landscape units in both models.

Amalgamation of soil drainage classes

The mean target soil property data associated with the modified drainage classes (Chapter 5, section 5.3.2.1) indicated that it would be appropriate to amalgamate the four soil drainage classes into two broad drainage classes: 'Dry soils' and 'Wet soils'. These classes are defined in section 4.3.1.3. The broad soil drainage class data were then grouped by landscape unit and the dominant broad drainage class in each unit was identified.

Definition of the soil-landscape units

Each landscape unit was assigned to one of two soil-landscape units (Dry or Wet) according to the dominant (representing more than 50% of the total number of observations made in that unit) broad drainage class that occurred within it. For example, a landscape unit comprising 80% Dry soils would be assigned to the Dry soil-landscape unit. The soil-landscape units are assumed to be uniform in terms of soil drainage for the purposes of applying and validating the models.

4.2.5 Model application and validation

The soil-landscape models were applied within their respective plots by assigning each data point (development and validation) to a soil-landscape unit. The soil-landscape units were assigned according to the landscape units on which the data points were known to have occurred. Broad soil drainage class was, in effect, predicted at each point. Predictions were made at all points (development and validation) for mapping purposes (sections 4.2.6 and 4.3.4). However, the prediction performance of the models was only assessed using the validation set data points.

The soil-landscape models were validated within their respective plots using the 62 data points of the corresponding validation set. Validation involved the comparison of observed broad drainage class with predicted broad drainage class (as indicated by the soil-landscape unit) at each validation point. If, at a given validation point, the predicted broad drainage class matched the observed then a correct prediction was registered. If the predicted and observed drainage classes did not match, an incorrect prediction was registered. The numbers of correct and incorrect predictions across the validation set were tallied and expressed as a proportion of the total number of validation points (section 4.3.5).

4.2.6 Spatial representation of the models

The application of the soil-landscape models across their respective plots allowed for the spatial distribution of the broad soil drainage classes predicted in each plot to be mapped (section 4.3.4) as soil-landscape units. The maps were developed in ARCGIS by interpolating the soil-landscape unit identification numbers (the soil-landscape units were represented by a value of either 1 or 2 in the attribute tables of the sample point coverages). The interpolation was performed using the Inverse Distance Weighted (IDW) technique available in the *spatial analyst* tool of ARCMAP to produce grids of the soil-landscape unit data. The resulting grids (consisting of continuous data) were classified, using the *spatial analyst* tool, into two discrete classes representing the two soil-landscape units before being converted into polygon shape-files (using the *spatial analyst* tool). The polygon shape-files were then converted to polygon coverages using the conversion tools in ARCTOOLBOX.

A map showing the spatial distribution of predicted broad soil drainage classes across southern Mahurangi Forest was also produced using ARCGIS and ARCMAP (Appendix Two). This map was created by applying a simplified version of the pre-harvested plot model in which broad drainage class was predicted on the basis of relative elevation class alone (section 4.2.4.3). That is, where the relative elevation class was high, Dry soils were predicted, and where the relative elevation class was low, Wet soils were predicted. A simplified version of the pre-harvested model was used because it could be rapidly and conveniently applied across the forest. The process of creating this map was essentially the same as that used in the creation of the predicted broad drainage class maps described above except that it was begun by classifying the pre-existing relative elevation grid into the high and low classes.

4.3 Results and discussion

The two principal constituents of the soil-landscape models, the soil drainage classes and the landscape frameworks, are described in detail before the soil-landscape models are characterised. The application of the models is examined prior to the evaluation of their predictive performance. At all stages the plots/models are compared and contrasted and the impacts of forest harvesting identified and interpreted.

4.3.1 The soils of southern Mahurangi Forest

The soils of southern Mahurangi Forest are described in three stages. Firstly, the subgroups of the NZSC identified within the forest are outlined. Secondly, the modified soil drainage classes used in the establishment of the soil-landscape relationships are defined and described. Thirdly, the amalgamation of the modified drainage classes into broad soil drainage classes is discussed. The differences between the plots in terms of the abundance of the drainage classes and NZSC subgroups are also considered.

Note that the term ‘low-chroma’ used below refers to greyish matrix colours with a moist chroma of 2 or less or a chroma of 3 with a value of 6 or more. Also, the term ‘upper part of the profile’ is used to refer to those parts of the profile within either 30 cm of the mineral soil surface or within 15 cm from the base of the A horizon. Furthermore, it should be noted that all values describing the abundance of the various NZSC and soil drainage classes given below were calculated using only the development set data for each plot.

4.3.1.1 Subgroups of the NZSC

The NZSC is a hierarchical classification system consisting of three primary levels. At the broadest level is the soil order which is subdivided into various groups at the second level. The groups are further subdivided into subgroups on the basis of more and more detailed soil information. The subgroups constitute the third level of hierarchy. There is a fourth, more specific, level in the hierarchy called the 'soilform'. Although all profiles were described to the soilform level (Appendix One), this category was not employed in the soil-landscape modelling process because the scoping study showed that it did not highlight any useful soil differences. Further mention of the soilform is made in Chapter 5 (section 5.3.3).

Four soil orders are represented within the study area: Ultic, Gley, Recent, and Raw soils. The identified soil classes (broken-down by hierarchical level) are tabulated below (Table 4.1).

Table 4.1. The soil classes of the NZSC identified within southern Mahurangi Forest.

Order	Group	Subgroup
Ultic	Perch-gley	Typic (UPT)
	Yellow	Mottled (UYM)
		Typic (UYT)
Gley	Orthic	Argillic (GOJ)
Recent	Fluvial	Mottled-acidic (RFMA)
	Orthic	Acidic (ROA)
		Mottled (ROM)
Raw	Gley	Fluid (WGF)
		Typic (WGT)
	Fluvial (WF)	

Ultic Soils

Ultic Soils are acidic and have clayey subsoils that show evidence of the translocation (illuviation) of clay or organic matter, or both (e.g. clay or humus coatings on ped faces). Thus, argillic (Bt) horizons are often identified within the subsoil. Profiles are usually slowly permeable (most are either imperfectly or poorly drained according to existing criteria) and surface horizons are susceptible to compaction. Most Ultic Soils are developed from clay-rich material weathered from acid igneous or siliceous sedimentary rocks. Strong weathering often results in low levels of reserve nutrients such as phosphorus, potassium and magnesium. Aluminium toxicity, resulting from the low pH, may restrict root growth. Surface horizons are susceptible to erosion because they tend to be dispersible (Hewitt, 1998).

Two groups of the Ultic order are represented within the forest: Yellow Ultic Soils and Perch-gley Ultic Soils. The Yellow Ultic Soils are clayey, well to imperfectly drained (according to existing criteria), and do not have thick E horizons or densipans. Two subgroups of the Yellow Ultic Soils have been identified, Mottled Yellow Ultic (UYM) Soils and Typic Yellow Ultic (UYT) Soils. The UYM Soils are imperfectly drained (according to existing criteria) and are characterised by a mottled profile form. A mottled profile form is defined by the presence of either a redox-mottled horizon (an horizon containing redox segregations or redox depletions, or both) in the upper part of the profile or a reductimorphic horizon (an horizon with a matrix dominated by low-chroma colours) deeper in the profile (between 30 and 60 cm). The UYT Soils are well to moderately well drained and have no aberrant properties (Hewitt, 1998). The Perch-gley Ultic Soils are poorly to very poorly drained and are characterised by a gley profile form in which a reductimorphic horizon occurs in the upper part of the profile as the result of water perching on a slowly permeable horizon. Perch-gley Ultic Soils are represented by a single subgroup within the forest, Typic Perch-gley Ultic (UPT) Soils. The UPT Soils have no aberrant properties (Hewitt, 1998).

Gley Soils

Gley Soils are poorly to very poorly drained soils that are usually characterised by a gley profile form in which the reductimorphic horizons extend from within the upper part of the profile to the base of the solum or to 90 cm depth. The poor drainage and consequent lack of aeration leads to limited rooting depths. Trafficability is also likely to be limited. Gley Soils are often formed in alluvium or colluvium that has accumulated in the lower parts of the landscape (Hewitt, 1998).

Within the study area, a single group, Orthic Gley Soils, represents the Gley Soil order. Orthic Gley Soils are Gley Soils that occur on stable geomorphic positions and do not receive regular additions of sediment. Orthic Gley Soils lack fine sedimentary stratification and oxidic horizons and are not sulphuric, acidic ($pH \leq 4.8$), or sandy. The Orthic Gley Soils are represented within the forest by a single subgroup, the Argillic Orthic Gley (GOJ) Soils. GOJ Soils are Orthic Gley Soils that contain an argillic horizon (Hewitt, 1998).

Recent Soils

Recent Soils are weakly developed, usually but not exclusively, as the result of relatively recent erosion or deposition, or both. Weathering-resistant parent materials may, in some cases, be responsible for the weak soil development. A distinct topsoil (A horizons that are 5 cm or more thick and are darker than the underlying horizon) has developed but a weathered B horizon is thin (less than 10 cm), if present at all. Where the soil is saturated, the upper part of the profile has developed to the extent that it is no longer fluid. Recent Soils are often more weakly leached (base saturations are higher) than other soils on similar landscape positions (e.g. Ultic Soils on steep slopes) and consequently have higher nutrient levels. Profiles are well to imperfectly drained (according to existing criteria), never poorly or very poorly drained, and rooting depths are usually deep (Hewitt, 1998).

Two groups of the Recent Soils order were identified within the study area, Fluvial Recent Soils and Orthic Recent Soils. Fluvial Recent Soils are formed from sediments that have been transported and deposited by streams or rivers (alluvium). They are defined and characterised by the presence of fluvial features which include buried A horizons (or an irregular distribution of carbon within the profile) and sedimentary stratification in C horizons. At the subgroup level, the Fluvial Recent Soils are represented in the study area by the Mottled-acidic Fluvial Recent (RFMA) Soils. The RFMA Soils are characterised by a mottled profile form and a $pH < 5.5$ within 60 cm of the soil surface (Hewitt, 1998). Orthic Recent Soils tend to occur on either eroding landforms or on side-slope positions that receive colluvial material from further upslope. They are not predominantly sandy and do not contain fluvial features, tephric soil material, a shallow lithic or paralithic contact, or evidence of hydrothermal activity. Two

Orthic Recent subgroups occur in the forest, Mottled Orthic Recent (ROM) Soils and Acidic Orthic Recent (ROA) Soils. The ROM Soils are imperfectly drained (according to existing criteria) and are characterised by a mottled profile form whereas the ROA Soils are well to moderately well drained and have subsoils with a pH of < 5.5 (Hewitt, 1998).

Raw Soils

Raw Soils are distinguished from Recent Soils by the absence of distinct topsoils or, in some cases, by the presence of fluid horizons in the upper part of the profile. The formation of topsoils is often inhibited in landscape positions experiencing recent erosion or deposition whereas very wet and constantly saturated landscape positions may result in the formation of fluid horizons. Pedogenic horizons such as a weathered-B horizon are absent and the materials in which the Raw Soils are formed are either fresh or weakly weathered. Consequently, levels of plant-available nutrients are often low (Hewitt, 1998).

The Raw Soil order is represented by two groups within the study area: the Gley Raw Soils and the Fluvial Raw (WF) Soils. Gley Raw Soils are saturated for substantial periods of time and, as a consequence, possess a gley profile form and are designated as poorly or very poorly drained. In contrast, the WF Soils are not poorly drained and have formed from relatively fresh alluvial sediments. They are defined by the presence of fluvial features and no subgroups of the WF group are recognised in the NZSC. The WF Soils identified in the study area are very similar to the RFMA Soils in terms of profile morphology — the presence or absence of a distinct topsoil horizon is the only differentiating feature. Hence, for the purposes of this study, the WF Soils are considered together with the RFMA Soils to be a single subgroup (RFMA/WF) from this point forward. Two subgroups of the Gley Raw Soils were identified within the forest, the Fluid Gley Raw (WGF) Soils and Typic Gley Raw (WGT) Soils. The WGF Soils have a moderately fluid to very fluid horizon in the upper part of the profile whereas the WGT Soils have no aberrant properties (Hewitt, 1998).

Redox-mottled and reductimorphic horizons

Redox-mottled horizons are hydromorphological indicators of alternating periods of saturation with water and subsequent desaturation. The redox segregations (present mainly in the form of orange coloured ferruginous mottles or black manganese concretions) indicate the migration and accumulation of reduced iron and manganese compounds and their subsequent oxidation during unsaturated periods (Vepraskas, 1994). In contrast, the redox depletions (present mainly in the form of greyish coloured mottles) that sometimes occur within redox-mottled horizons represent the reduction and removal of iron and manganese compounds (with or without clay particles) at spatially discrete locations within the horizon during periods of saturation (Birkeland, 1999). Therefore, it is likely that the redox-mottled horizons that contain redox depletions are reduced for somewhat longer periods than those that contain redox segregations alone (Vepraskas, 1994; Birkeland, 1999). Hence, the presence of redox depletions in the upper part of the profile may indicate more impeded soil drainage conditions than the presence redox segregations alone. The horizon nomenclature used in New Zealand (Clayden and Hewitt, 1994) makes the distinction between redox mottled horizons that contain only redox segregations, designated '(f)', and those that also contain redox depletions, designated '(g)'.

Reductimorphic horizons are indicators of prolonged saturation with water. Under the strongly reduced conditions that result from prolonged saturation, much of the iron occurs in reduced forms and so low-chroma colours predominate (Vepraskas and Sprecher, 1997). Redox segregations may also occur within a reductimorphic horizon (Vepraskas and Sprecher, 1997).

Strong relationships between the duration of saturation and the presence, location (in the profile), and abundance of the hydromorphological indicators mentioned above have been found in previous studies (e.g. Hseu and Chen, 2001; Jacobs *et al.*, 2002; He *et al.*, 2003).

The abundance of orders and subgroups

The abundance with which the most common orders and subgroups of the NZSC occur differs slightly between the plots (Table 4.2).

Table 4.2. Abundance of NZSC orders and subgroups in both plots.

		Abundance (%)	
	Soil classes	**Pre-harvested plot**	**Post-harvested plot**
Orders	Ultic	88	92
	All others (Table 4.1)	12	8
Subgroups	UYT	27	17
	UYM	50	71
	UPT	11	5
	All others (Table 4.1)	12	8

The majority of soils in the study area are of the Ultic order. The Ultic Soils account for 88% of observations in the pre-harvested plot and about 92% in the post-harvested plot. The UYM subgroup is the most commonly occurring subgroup in both plots, with 50% of the observations in the pre-harvested plot and 71% in the post-harvested plot classified as UYM Soils. The UYT subgroup is the second most common, accounting for 27% of observations in the pre-harvested plot and 17% in the post-harvested plot. All other subgroups, with the exception of the UPT Soils which account for 11% of observations in the pre-harvested plot, occur infrequently (individually accounting for around 5% of observations, or less).

4.3.1.2 Modified soil drainage classes

The modified soil drainage classes, defined below, are essentially used as a local soil classification for the purposes of this study. That is, they are the selected locally significant soil classes. The hydromorphological criteria used to assign soils to the modified drainage classes are outlined and the proportions of observations of a particular drainage class accounted for by the various NZSC subgroups they encompass are given. The variation in profile morphologies within the drainage classes is described using the horizonation found to be typical of the constituent NZSC subgroups. Full descriptions of the key soil profiles, presented below as examples of the dominant subgroups within the drainage classes (Figures 4.5-4.8), are given in Appendix One.

The modified soil drainage classes and their constituent NZSC subgroups are summarised together with the Soil Taxonomy subgroups and soil series that correspond to the NZSC subgroups (Table 4.3).

Table 4.3. Modified soil drainage classes, their constituent NZSC subgroups, and corresponding Soil Taxonomy subgroups and soil series.

Modified drainage classes	NZSC subgroups	Soil Taxonomy subgroups*	Soil series
Well Drained	UYT†	Typic Hapludults	Warkworth
	ROA	Typic Dystrudepts‡	Atuanui
Imperfectly Drained	UYM1†	Typic Hapludults	Whangaripo
	ROM1	Oxyaquic Dystrudepts‡	Atuanui
Somewhat Poorly Drained	UYM2†	Aeric Endoaquults	Puhoi
	ROM2	Aquic Dystrudepts‡	Atuanui
	RFMA/WF	Aeric Fluvaquents	Whakapara
Poorly Drained	UPT†	Aeric Epiaquults	Pohuehue§
	GOJ†	Typic Endoaquults	Kara
	WGF	Typic Hydraquents‡	Hungry Creek§
	WGT	Typic Endoaquents‡	Hungry Creek§

* Soil Survey Staff (1999). † Key profiles given below as examples of these soils (Figures 4.5-4.8). ‡ Classifications based on auger observation data alone. § Proposed series — defined in this study (Chapter 3, section 3.4.1.7).

Well Drained soils

The Well Drained soils include the well and moderately well drained soils of the existing soil drainage criteria and are defined to be soils that have *either*:

1. no horizon with an upper boundary within 90 cm of the mineral soil surface that contains either (a) ≥ 2% redox segregations or (b) ≥ 2% redox depletions, *or*
2. an horizon with an upper boundary between 30 and 90 cm from the mineral soil surface that contains either (a) ≥ 2% redox segregations or (b) ≥ 2% but < 50% redox depletions (i.e. a redox-mottled horizon), *or*
3. an horizon with an upper boundary between 60 and 90 cm from the mineral soil surface that contains ≥ 50% low-chroma colours (i.e. a reductimorphic horizon) (Milne *et al.*, 1995).

Two NZSC subgroups are encompassed by the composite Well Drained class, the UYT and ROA Soils. The majority of the Well Drained soils within both plots are UYT Soils with the ROA Soils accounting for only 11% of the Well Drained soils observed in the pre-harvested plot and 4% of those observed in the post-harvested plot. Therefore, the profile selected to represent the Well Drained class is representative of many of the UYT Soils in the forest (Figure 4.5).

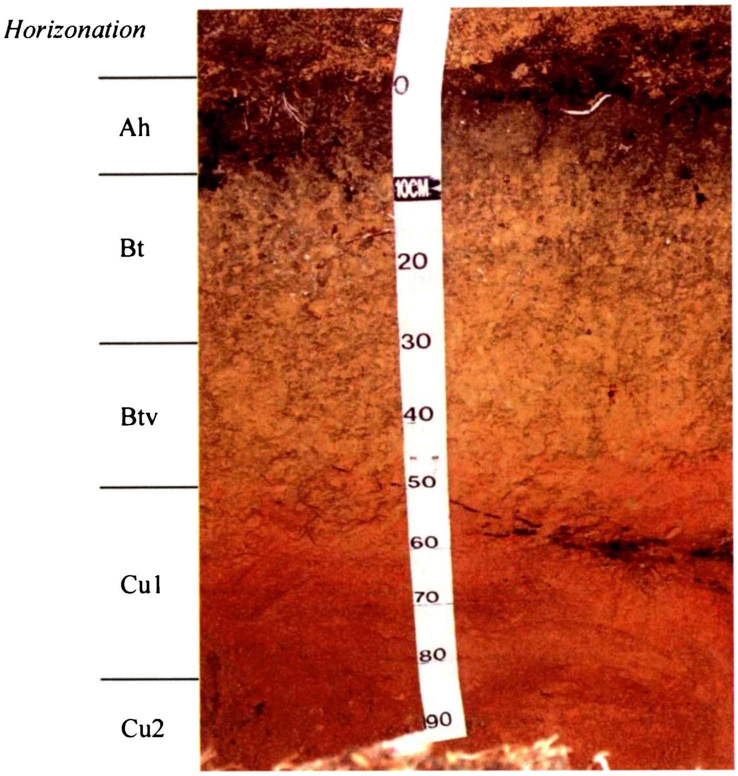


Figure 4.5. Profile 1: an example of a typical Well Drained soil (NZSC: UYT, Soil Taxonomy: Typic Hapludults, Soil series: Warkworth). Note that the reddish saprolite occurs at about 50 cm depth which indicates that this is an example of a Well Drained soil of the shallow, drier profile type.

The UYT Soils have a thin (~ 8 cm on average), dark-yellowish brown AB or A/B topsoil horizon that overlies one to two yellowish-brown argillic (Bt) horizons with an average total thickness of ~ 50 cm. One or two brownish-yellow BC horizons usually represent the transition between the argillic horizons and the underlying Cu horizons. Approximately half of the UYT Soils are formed from red to yellowish-red Cu material (reddish saprolite) and the remainder are formed from yellowish-brown Cu material (yellowish saprolite). The UYT Soils within the study area are classified as Typic Hapludults using Soil Taxonomy and correlate with the Warkworth series (Chapter 3, section 3.4.1.1).

There is some variation in profile morphology within the UYT subgroup. The subsoils of profiles classified as moderately well drained under the existing drainage criteria (representing a slightly wetter profile type) are generally characterised by a Bt horizon in the upper part of the profile that overlies a Bt(f) or, in some cases, a Bt(g) horizon. Horizons with the designation '(f)' contain ≥ 2% redox segregations whereas those with the designation '(g)' contain ≥ 2% but < 50% redox depletions in addition to ≥ 2% redox segregations (following Clayden and Hewitt, 1994). Underlying the argillic horizons are BC(f) or BC(g) horizons. In contrast, the subsoils of profiles classified as well drained under the existing drainage criteria (representing a slightly drier profile type) usually comprise a Bt horizon overlying a Btv horizon that grades into a BC or BCv horizon. For the purposes of this study the designation 'v' indicates that a horizon contains reddish coloured mottles that are remnants of the reddish saprolite from which they have formed. The average total thickness of the argillic horizons in the wetter profile type (~ 60 cm) is greater than that of the argillic horizons in the drier profile type (~ 40 cm). Therefore, the profiles of the drier profile type tend to be shallower (Figure 4.5) than those of the wetter profile type and have a relatively thin solum and a Cu horizon (usually saprolite or saprolite-derived material) commensurately fairly close to the soil surface (typically at ~ 50 cm depth).

The ROA Soils have profile morphologies characterised by a very thin (~ 5 cm), dark-yellowish brown AB or A/B topsoil horizon that often directly overlies a brownish-yellow BC or red to yellowish-red Cu horizon. Most (~ 70%) ROA Soils were formed from reddish saprolite. In some cases, a thin (< 10 cm) or shallow (lower boundary does not extent beyond 30 cm depth), yellowish-brown weathered-B (Bw or Bt) horizon may occur below the topsoil. The ROA Soils probably represent UYT profiles that have been truncated by erosion. Within the study area the ROA Soils are classified as Typic Dystrochrepts according to Soil Taxonomy and correspond to the Atuanui series (Chapter 3, section 3.4.1.5).

Imperfectly Drained soils

The Imperfectly Drained soils include some of the imperfectly drained soils of the existing soil drainage criteria and are redefined here to be soils that have:

1. an horizon with an upper boundary within either (a) 15 cm of the base of the A horizon, or (b) 30 cm of the mineral soil surface that contains ≥ 2% redox segregations (Milne *et al.*, 1995).

Included in the Imperfectly Drained class are two NZSC subgroups, the UYM and ROM Soils. However, not all UYM and ROM Soils are included — only those with a redox-mottled horizon in the upper part of the profile that contains redox segregations alone (i.e. < 2% redox depletions). These soils, designated here as UYM1 and ROM1, have a hydromorphology indicative of drier conditions than those of the Somewhat Poorly Drained UYM and ROM soils (designated UYM2 and ROM2 in the following section). In essence, two hydromorphologically distinct profile types were recognised among the UYM and ROM Soils of the forest: a drier profile type represented by the Imperfectly Drained class (UYM1 and ROM1 Soils) and a wetter profile type represented by the Somewhat Poorly Drained class (UYM2 and ROM2 Soils).

All of the Imperfectly Drained soils in the pre-harvested plot and almost all of those in the post-harvested plot are UYM1 Soils. The ROM1 Soils account for only 3% of the Imperfectly Drained soils observed in the post-harvested plot. Thus, the profile selected to represent the Imperfectly Drained class is an example of a typical UYM1 Soil (Figure 4.6).

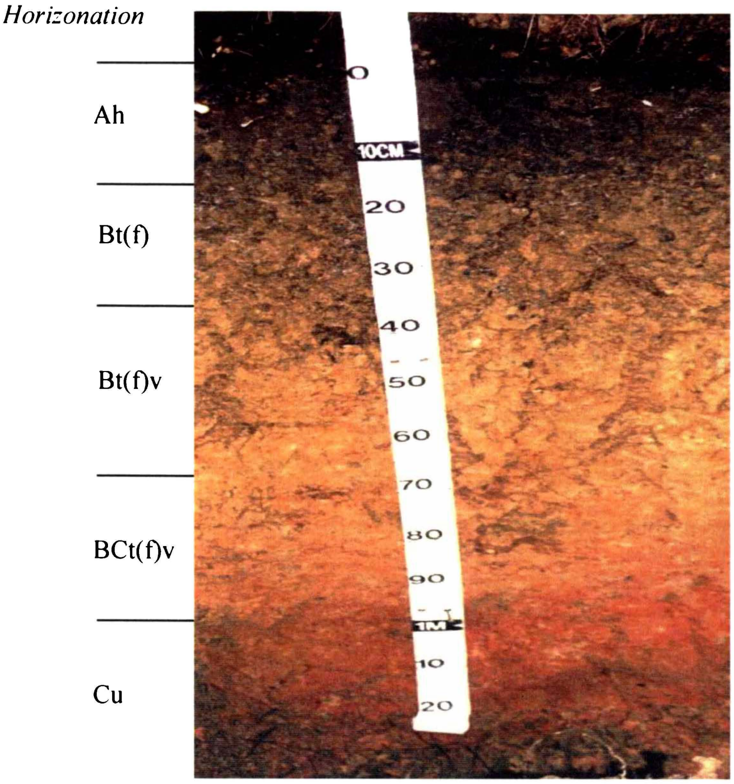


Figure 4.6. Profile 2: an example of a typical Imperfectly Drained soil (NZSC: UYM1, Soil Taxonomy: Typic Hapludults, Soil series: Whangaripo). Note that the reddish saprolite (Cu horizon) occurs at about 100 cm depth and redox segregations are common in the Bt horizons (c.f. Profile 1, Figure 4.5).

The UYM1 Soils are characterised by a thin (~ 6 cm on average), dark yellowish-brown AB or A/B topsoil horizon that overlies two to three yellowish-brown Bt(f) argillic horizons which extend from the upper part of the profile to the base of the weathered-B horizon. The argillic horizons have an average total thickness of ~ 50 cm. Brownish-yellow BC(f), BC(g), or BC(f)v horizons generally occur beneath the argillic horizons and grade into Cu horizons. About 50% of the UYM1 Soils are formed from reddish saprolite represented by red to yellowish-red Cu horizons. The other 50% had yellowish-brown Cu horizons indicative of the yellowish saprolite. The saprolitic material tends to occur at greater depths (~ 100 cm) in the profiles of the UYM1 Soils than it does in the (Well Drained) UYT Soils of the drier profile type because of the greater thickness of the argillic and BC horizons in the UYM1 Soils. These (Imperfectly Drained) UYM1 Soils are classified as Typic Hapludults using Soil Taxonomy and correlate with the Whangaripo series (c.f. the UYM2 Soils) that has been mapped previously in the area (Chapter 3, section 3.4.1.2). Note that Soil Taxonomy recognises the morphological similarities between the UYM1 Soils and the (Well Drained) UYT Soils (both are assigned to the same subgroup) and emphasises the differences between the UYM1 and UYM2 Soils (different at the suborder level).

The ROM1 Soils have profile morphologies slightly different from those of the UYM1 subgroup. A thin (< 10 cm), dark yellowish-brown AB topsoil horizon directly overlies brownish-yellow BC(f) or BC(f)v horizons which, in turn, overlie red to yellowish-red Cu horizons (i.e. all were formed from reddish saprolite). The ROM1 Soils lack argillic horizons and are probably UYM1 profiles that have been truncated by erosion. Within the study area, the ROM1 Soils are classified as Oxyaquic Dystrochrepts according to Soil Taxonomy and, in this study, are correlated to the Atuanui series (Chapter 3, section 3.4.1.5).

Somewhat Poorly Drained soils

The Somewhat Poorly Drained soils include some of the imperfectly drained soils of the existing soil drainage criteria and are defined to be soils that have *either*:

1. an horizon with an upper boundary within either (a) 15 cm of the base of the A horizon, or (b) 30 cm of the mineral soil surface that contains ≥ 2% but < 50% redox depletions, *or*
2. an horizon with an upper boundary between 30 and 60 cm from the mineral soil surface, but not within 15 cm of the base of the A horizon, that contains ≥ 50% low-chroma colours (Milne *et al.*, 1995).

Comprising the Somewhat Poorly Drained class are three subgroups of the NZSC: the UYM2, ROM2, and RFMA/WF Soils. All of these are of the wetter profile type (c.f. Imperfectly Drained) meaning that the redox-mottled horizon in the upper profile contains ≥ 2% but < 50% redox depletions or that there is a reductimorphic horizon deeper in the profile (between 30-60 cm). The Somewhat Poorly Drained class is dominated by UYM2 Soils within both plots with only minor representation of the ROM2 and RFMA/WF subgroups. In the pre-harvested plot, the ROM2 and RFMA/WF Soils account for 5% and 2% of the observed Somewhat Poorly Drained soils, respectively. The ROM2 Soils are absent from the post-harvested plot but the RFMA/WF Soils were slightly more common than they were in the pre-harvested plot, accounting for 6% of the Somewhat Poorly Drained soils observed in that plot. The profile selected to represent the Somewhat Poorly Drained class is an example of a typical UYM2 Soil (Figure 4.7).

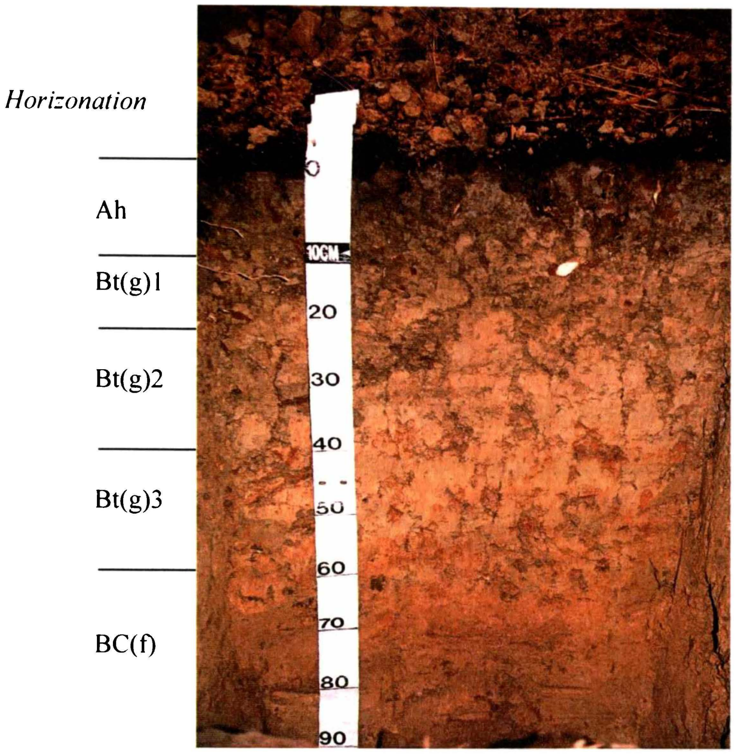


Figure 4.7. Profile 3: an example of a typical Somewhat Poorly Drained soil (NZSC: UYM2, Soil Taxonomy: Aeric Endoaquults, Soil series: Puhoi). Redox segregations and redox depletions occur in the Bt horizons. Note that the saprolite is yellowish rather than reddish.

The UYM2 Soils have a thin (~ 8 cm), dark brown AB, A/B, or AB(g) topsoil horizon that overlies two to three predominantly light yellowish brown Bt(g) argillic horizons. Some profiles may contain some Bt(f) horizons but all have a Bt(g) horizon in the upper part of the profile. The argillic horizons have an average total thickness of ~ 45 cm. Brownish-yellow to yellowish-brown BC(g) or BC(f) horizons usually occur beneath the argillic horizons and overlie pale yellow to yellowish-brown Cu horizons. Almost 90% of the UYM2 Soils were formed from yellowish saprolite. A lithic or paralithic contact (R or CR horizon, respectively) was found within 120 cm depth in some cases. These (Somewhat Poorly Drained) UYM2 Soils are classified as Aeric Endoaquults using Soil Taxonomy and, in this study, are correlated to the Puhoi series (c.f. the UYM1 Soils) (Chapter 3, section 3.4.1.3). Note that Soil Taxonomy recognises the morphological similarities between the UYM2 Soils and the (Poorly Drained) UPT and GOJ Soils (by assigning these soils to the same suborder).

The fluvial origin of the materials forming the RFMA/WF Soils has caused their profile morphologies to be fairly variable. The RFMA/WF Soil profiles essentially consist of a series of pale yellowish-brown to greenish-grey, loamy BC, BC(g), BCg, or BCr horizons. Horizons that carry the designation 'g' are reductimorphic horizons in which 50-85% of the matrix is occupied by low-chroma colours and in which there are more than 2% redox segregations. Horizons with the designation 'r' are intensely gleyed reductimorphic horizons that contain > 85% low-chroma colours in the matrix. The RFMA Soils contain a dark yellowish-brown AB or AC topsoil horizon (qualifying as a distinct topsoil) which occurs at the soil surface or is buried with its upper boundary within 60 cm of the mineral soil surface. Where a distinct topsoil horizon is absent the profile is classified as a WF Soil. In all cases a BC(g) horizon occurs within the upper part of the profile and the reductimorphic horizons, if present, occur deeper in the profile (between 30 and 60 cm). The RFMA/WF Soils within the study area are classified as Aeric Fluvaquents according to Soil Taxonomy and are correlated to the Whakapara series (Chapter 3, section 3.4.1.6).

The ROM2 Soils have a thin (< 10 cm) AB topsoil horizon and no argillic horizons. Brownish-yellow to yellowish-brown BC(g) horizons occur within the upper part of the profile and overlie pale yellow to yellowish-brown BC or Cu horizons All were formed from yellowish saprolite. These soils probably represent UYM2 Soils that have been truncated by erosion. Within the study area, the ROM2 Soils are classified as Aquic Dystrochrepts according to Soil Taxonomy and, in this study, are correlated to the Atuanui series (Chapter 3, section 3.4.1.5).

Poorly Drained soils

The Poorly Drained soils include the poorly and very poorly drained soils of the existing drainage criteria and are defined to be soils that have *either*:

1. a distinct topsoil (Hewitt, 1998) and a horizon with an upper boundary within either (a) 15 cm of the base of the A horizon, or (b) 30 cm of the mineral soil surface that contains ≥ 50% low-chroma colours, *or*
2. no distinct topsoil and a horizon with an upper boundary within 30 cm from the mineral soil surface that contains ≥ 50% low-chroma colours, *or*

3. an O horizon with an Er, Br, or Cr horizon directly below (Milne *et al.*, 1995).

The UPT, GOJ, WGF, and WGT subgroups of the NZSC are encompassed by the composite Poorly Drained class. UPT Soils predominate in both plots, accounting for 62% of the Poorly Drained soils observed in the pre-harvested plot and 54% of those observed in the post-harvested plot. However, the GOJ Soils are also relatively common, accounting for 31% of the Poorly Drained soils observed in both plots. The WGF soils account for 8% of the Poorly Drained soils in the pre-harvested plot but are absent from the post-harvested plot whereas the WGT soils are absent from the pre-harvested plot but account for 15% of the Poorly Drained soils in the post-harvested plot. Two profiles were selected to represent the Poorly Drained class (Figures 4.8a and b) reflecting the fact that two NZSC subgroups are fairly common within this composite drainage class. Figure 4.8a is an example of a typical UPT profile whereas Figure 4.8b represents the GOJ Soils.

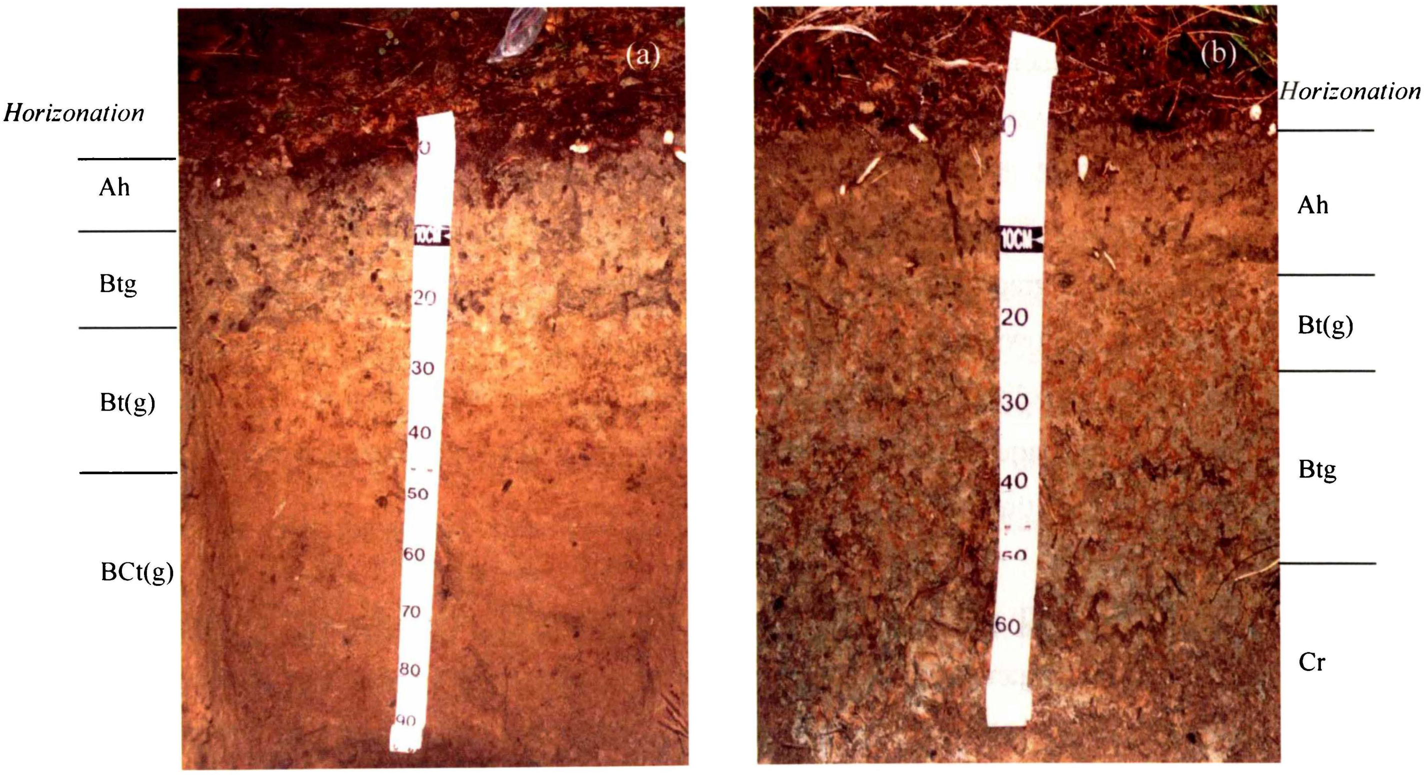


Figure 4.8. Examples of the two most common Poorly Drained soils: (a) Profile 4: an example of a typical UPT Soil (Soil Taxonomy: Aeric Epiaquults, Soil series: Pohuehue) and (b) Profile 5: an example of a typical GOJ Soil (Soil Taxonomy: Typic Endoaquults, Soil series: Kara). Note the reductimorphic horizon occurring at 10-25 cm depth in Profile 4. Low-chroma colours dominate the matrix from a depth of about 25 cm in Profile 5.

The UPT Soil profiles consist of a thin (~ 10 cm), light olive-brown Ap or AB(g) horizon which overlies two to three Bt horizons with a mean total thickness of ~ 50 cm. Pale olive Btg (reductimorphic) horizons occur in the upper part of the profile whereas the deeper argillic horizons are commonly yellowish-brown Bt(g) horizons. Underlying the argillic horizons are usually a couple of yellowish brown BC(g) horizons that grade into pale yellow or yellowish brown Cu horizons. The majority (~ 90%) of UPT Soils are formed from yellowish saprolite. The fact that the reductimorphic horizons do not extend to the base of the B horizon in these soils indicates that the water table is perched on an impermeable layer within the profile. The UPT Soils within the study area are classified as Aeric Epiaquults using Soil Taxonomy and are correlated to the newly defined Pohuehue series (Chapter 3, section 3.4.1.7).

The GOJ Soils have a relatively thick (~ 12 cm on average), dark brown Ap or AB topsoil horizon. In some profiles either an Ap(g), ABg, or AB(g) topsoil horizon was identified. One to two greyish-olive Btg or Btr horizons occur beneath the topsoil or, in some cases, beneath a thin yellowish-brown Bt(f) or Bt(g) horizon. In every case a reductimorphic horizon occurs within the upper part of the profile and extends to the base of the solum. The mean total thickness of the argillic horizon is ~ 50 cm. Yellowish-brown BC(g) horizons underlie the argillic horizons and grade into either light greenish-grey Cr horizons or pale yellowish-brown to yellowish-brown Cu(g) horizons. All GOJ Soils were formed from yellowish saprolite. The GOJ Soils identified within the study area are classified as Typic Endoaquults according to Soil Taxonomy and correlate to the Kara series (Chapter 3, section 3.4.1.4).

All of the WGT and most of the WGF Soils lacked distinct topsoils. However, fluid, black, organic-rich AO topsoil horizons were found in some WGF profiles. These soils do not contain argillic horizons. However, a bluish-grey BCr horizon sometimes occurs above a CR or R horizon. The profiles of the WGT Soils are characterised by several greenish-grey BCg and light yellowish-brown BC(g) horizons that sometimes overlie deeply buried Btr material. All WGT and WGF profiles have a reductimorphic horizon within the upper part of the profile and all are formed from yellowish saprolite. The WGT Soils in the study area are classified as Typic Endoaquents according to Soil Taxonomy whereas the WGF Soils are classified as Typic Hydraquents and both are correlated to the newly defined Hungry Creek series (Chapter 3, section 3.4.1.8).

4.3.1.3 Amalgamation of the modified soil drainage classes

The modified soil drainage classes described above were amalgamated to form two broad soil drainage classes in order to improve the practicality of the soil-landscape models. Two broad soil drainage classes were defined: Dry soils and Wet soils. The Well and Imperfectly Drained soils were combined to form the Dry class whereas the Wet class encompasses the Somewhat Poorly and Poorly Drained soils (Table 4.4). The proportions of the broad drainage classes accounted for by the modified drainage classes are presented (Table 4.4).

Table 4.4. Abundances of modified soil drainage classes within broad classes in both plots.

		Abundance (%)	
Broad classes	**Modified drainage classes**	**Pre-harvested plot**	**Post-harvested plot**
Dry soils	Well Drained	56	27
	Imperfectly Drained	44	73
Wet soils	Somewhat Poorly Drained	61	73
	Poorly Drained	39	27

The Dry class is dominated by the Well Drained soils in the pre-harvested plot where 56% of observed Dry soils were of the Well Drained class. However, the Imperfectly Drained soils dominate the Dry class in the post-harvested plot where they account for 73% of observed Dry soils. The Somewhat Poorly Drained soils dominate the Wet class in both plots, accounting for 61% of the Wet soils observed in the pre-harvested plot and 73% of those in the post-harvested plot.

4.3.1.4 Differences in the abundance of broad and modified drainage classes between the plots

Although the same soil drainage classes occur in both plots, there are differences between the plots in terms of the abundance of these classes (Table 4.5).

Table 4.5. Abundances of the broad and modified soil drainage classes in both plots.

Drainage classes		Abundance (%)	
		Pre-harvested plot	**Post-harvested plot**
Broad classes	Dry soils	53	67
	Wet soils	47	33
Modified classes	Well Drained	30	18
	Imperfectly Drained	23	49
	Somewhat Poorly Drained	29	24
	Poorly Drained	18	9

The post-harvested plot is generally drier than the pre-harvested plot, with 67% of all observations classified as Dry soils. Just over half (53%) of the observations in the pre-harvested plot are classified as Dry soils. A possible explanation for the greater abundance of Dry soils in the post-harvested plot is given in section 4.3.2.4.

The differences can be examined in more detail by considering the abundances of the modified soil drainage classes (Table 4.5). The Imperfectly Drained soils are approximately twice as common in the post-harvested plot as they are in the pre-harvested plot. The abundances of the Well Drained and Poorly Drained soils in the post-harvested plot are roughly half those in the pre-harvested plot, whereas the abundance of the Somewhat Poorly Drained soils is similar in both plots. Almost half of the soils in the post-harvested plot are classified as Imperfectly Drained soils, clearly the most common drainage class in that plot. The lower abundance of the Well Drained soils and, to a certain extent, the greater abundance of Imperfectly Drained soils in the post-harvested plot, may be due to soil compaction caused by harvesting machinery. Data presented in Chapter 5 (section 5.3.1) show that soil macroporosity was reduced across the landscape due to harvesting activities. Well Drained soils that were compacted by harvesting vehicles or by logs being dragged along the ground may have become less permeable to water movement and consequently, could have developed redox segregations in their upper profiles. These soils would then have been identified as Imperfectly Drained. The modified drainage classes are more equally represented within the pre-harvested plot with only the Poorly Drained soils being substantially less common than the other classes which are similar in abundance

(Table 4.5). The much greater abundance of Imperfectly Drained soils in the post-harvested plot accounts for the greater abundance of Dry soils in that plot. The differences in the abundance of the drainage classes are reflected in the soil-landscape relationships of the models (section 4.3.3.1).

4.3.2 The landscape frameworks

The landscape frameworks of the soil landscape models are described below at two levels. Firstly, a detailed and hierarchical geomorphic subdivision of the landscape is presented in the form of the modified initial landscape framework. The modified initial landscape framework is identical for both models. Secondly, a broad hierarchical geomorphic subdivision of the landscape in each plot is presented in the form of the refined landscape frameworks. The refined landscape frameworks essentially represent the reformulation of the more detailed levels (elements and sub-elements) of the modified initial landscape framework into much broader geomorphic groupings. The refined landscape framework of each plot is identical except in the definitions of the most detailed subdivisions of the hierarchy.

4.3.2.1 The modified initial landscape framework

The modified initial landscape framework consists of a four-tiered hierarchy of geomorphic features. At the broadest level is the land system. The land system is defined to be the area of validity of a soil-landscape model (Lynn and Basher, 1994). It corresponds to an area in which there is a recurring pattern of vegetation, topography, and soils under a relatively uniform climate (Christian and Stewart, 1952). The land systems approach involves the hierarchical stratification of the landscape primarily on the basis of landform and it provides the framework within which soil-landscape models can be developed and applied (Lynn and Basher, 1994). Complex and simple land systems, as defined by Christian and Stewart (1952), may be recognised (e.g. Hill, 1999). However, southern Mahurangi Forest is situated on a single, simple land system. This land system was subdivided into land components at the second level. Land components consist of one or more land elements that constitute the third level in the hierarchy. At the fourth level, some of the land elements were further subdivided into land sub-elements. The land components, elements, and sub-elements were identified and defined on the basis of their morphology, relative position in the landscape, and presumed genesis.

For the purposes of this study, land components are defined to be widespread, broad geomorphic units that contain a recurring assemblage of land elements (e.g. ridge summits). Land components may be either discrete, contiguous geomorphic units (e.g. side-slopes) or an amalgamation of spatially separate land elements presumed to be formed by a similar geomorphic process (e.g. mudslide features). Land elements are areas between distinct breaks in slope steepness (Lynn and Basher, 1994) (e.g. backslopes distinguished from shoulder slopes) or are discrete geomorphic features that are genetically related to, and may be contained within, a land component (e.g. ridge summit hillocks), or both. The land sub-elements were defined on the basis of slope width (e.g. narrow ridge summit slopes) or relative landscape position (e.g. upper side-slope back-slopes).

The land system within which southern Mahurangi Forest is situated was described as stream-incised, gently rolling to very steep hill country (Chapter 3, section 3.3.4) (Kermode *et al.*, 1992; Edbrooke, 2001). Four land components were identified within the study area: (1) ridge summits (RS), (2) side-slopes (SS), (3) gully-floors (GF), and (4) mudslide features (MF). The side-slopes component is the most ubiquitous and widespread and probably accounts for the majority of land area within the study site. Ridge summits are widespread and occupy a substantial proportion of the study area also. Although widespread, gully-floors comprise only a small proportion of the land area. The two mudslide features identified (discrete geomorphic features thought to have formed due to mudsliding) range in size from relatively small (< 10 m across) to moderately large features (~100 m across) and occur sporadically, although not infrequently, throughout the forest. Side-slopes and ridge summits are considered major components whereas gully-floors and mudslide features are considered relatively minor components. The terminology used in the following description of the land components, elements, and sub-elements has been adapted from Milne *et al.* (1995) and the slope steepness classes used are consistent with those of the New Zealand Land Resource Inventory (NZLRI) (Harmsworth, 1996).

Representation of the modified initial landscape framework

The land elements and sub-elements described below and their relative positions in the landscape are illustrated using an idealised block diagram (Figure 4.9).

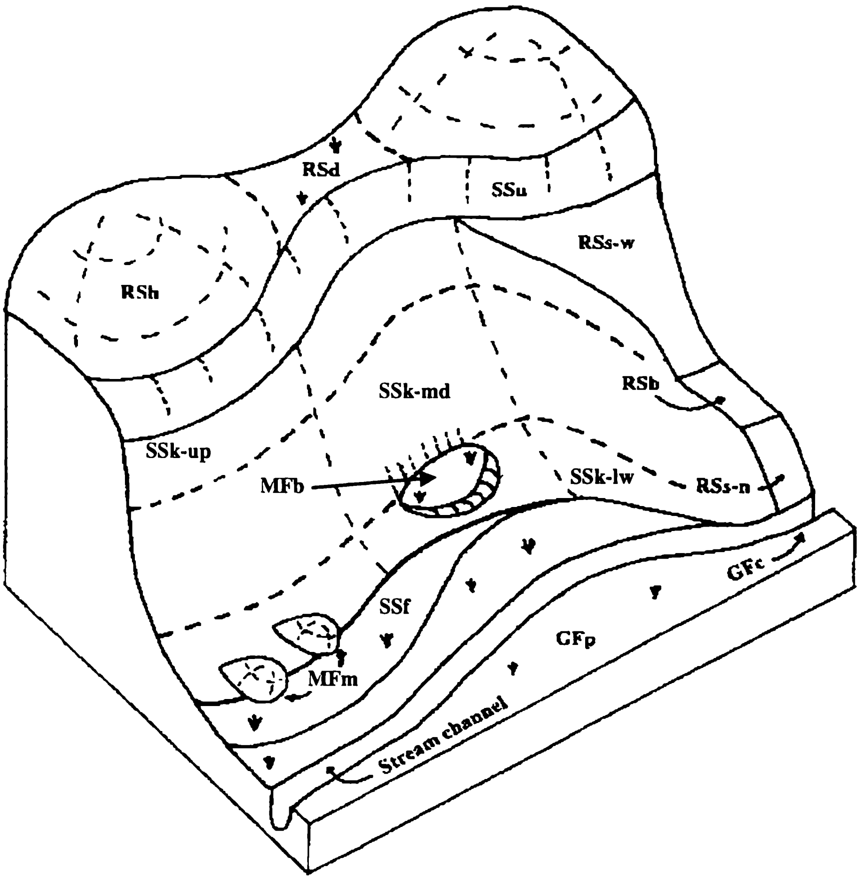


Figure 4.9. An idealised block diagram illustrating the nature and position of the land elements and sub-elements within both plots. Key: RSs-n = narrow ridge summit slopes, RSs-w = wide ridge summit slopes, RSb = ridge summit bench, RSh = ridge summit hillock, RSd = ridge summit saddle, SSu = side-slope shoulder, SSk-up = upper side-slope back-slope, SSk-md = middle side-slope back-slope, SSk-lw = lower side-slope back-slope, SSf = side-slope foot-slope, GFp = gully floor floodplain, GFc = gully floor channel, MFm = mudslide feature mound, MFb = mudslide feature bench.

Ridge summits

Ridge summits are areas of flat to rolling land (0-15°) occurring at the top of elongated hills (main ridges) or spurs (Figure 4.9). They comprise four land elements: (1) ridge summit slopes (RSs), (2) ridge summit benches (RSb), (3) ridge summit hillocks (RSh) and, (4) ridge summit saddles (RSd). Ridge summit slopes (Figure 4.10) include those parts of spur or main ridge summit areas that are sloping — undulating to rolling (4-15°). Ridge summit benches encompass the flat to gently undulating (0-3°) parts of a ridge summit (Figure 4.10). They commonly occur on narrow spur ridges and are often in between two sloping ridge summits, one above and one below. Ridge summits typically rise into rounded (convex profile and contour shape) mounds described here as ridge summit hillocks. Ridge summit saddles occur where two hillocks, in close proximity to one another, form a concave 'depression' between them. The ridge summit slope element was further subdivided into two sub-elements: narrow ridge summit slopes (RSs-n) and wide ridge summit slopes (RSs-w). Narrow ridge summit slopes have a width of 10 m or less whereas wide ridge summit slopes are wider than 10 m.

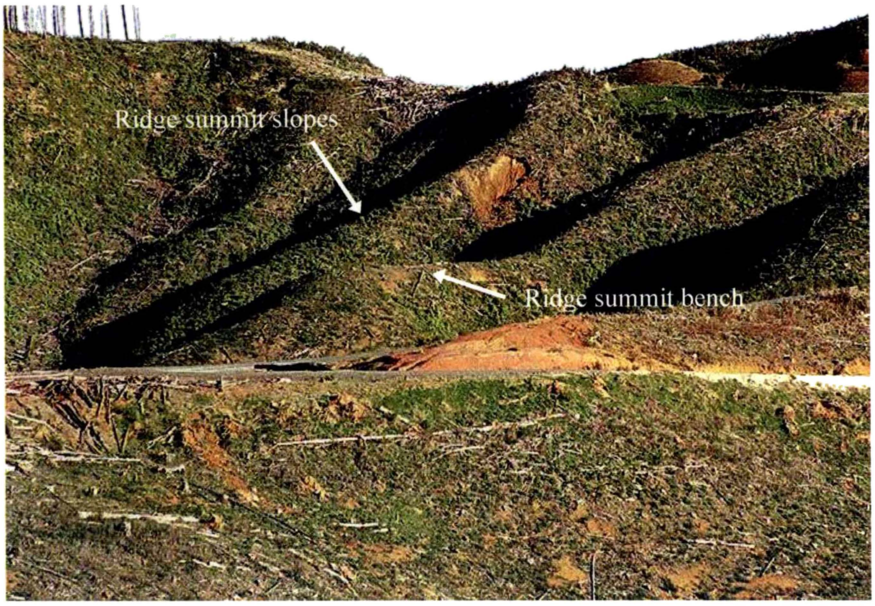


Figure 4.10. Ridge summit slopes and ridge summit benches in southern Mahurangi Forest.

Side-slopes

Side-slopes are hill slopes that, for the purposes of this study, are defined to occur between ridge summits and gully floors (Figure 4.9). This component is subdivided into three land elements: (1) side-slope shoulder-slopes (SSu), (2) side-slope back-slopes (SSk), and (3) side-slope foot-slopes (SSf). Side-slope shoulder-slopes (Figure 4.11) are convex slopes that occur immediately adjacent to ridge summits forming the uppermost part of the side-slope. Side-slope back-slopes (Figure 4.11) occupy the central parts of side-slopes that extend from the base of the shoulder-slope to the top of the foot-slope. The back-slope element usually encompasses the majority of the length of a side-slope. Side-slope foot-slopes (Figure 4.11) are the less steep and sometimes concave (in profile) lower parts of side-slopes that are bounded from above by back-slopes and from below by gully-floors. The side-slope back-slope element was further subdivided (in the process of refining the initial landscape framework) into three sub-elements on the basis of relative landscape position: (1) upper side-slope back-slopes (SSk-up), (2) middle side-slope back-slopes (SSk-md), and (3) lower side-slope back-slopes (SSk-lw). The upper back-slope sub-element represents approximately the upper 25% of the back-slope whereas the lower sub-element occupies approximately the lower 25% of the back-slope. The remaining central 50% of the back-slope, situated between the upper and lower portions, is represented by the middle sub-element.

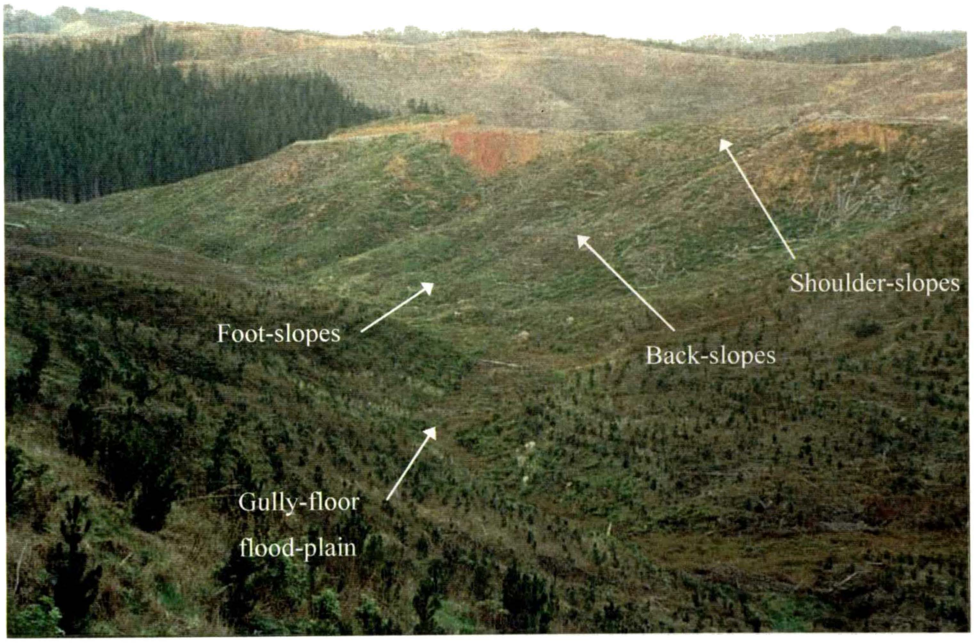


Figure 4.11. Side-slope shoulder-slopes, back-slopes, foot-slopes, and gully-floor flood-plains in southern Mahurangi Forest.

Gully floors

For the purposes of this study, gully-floors are defined to be the relatively narrow elongated strips of land lying between the bases of two side-slopes (Figure 4.9). They may contain either ephemeral to small streams or more substantial permanent streams ranging to small rivers. Two land elements of this component are recognised: (1) gully-floor flood-plains (GFp) and (2) gully-floor channels (GFc). Gully-floor floodplains (flat to concave, elongated strips of land adjacent to stream channels) (Figure 4.11) occur where the larger streams flow, which is usually within a higher-order gully or small valley (i.e. between two main ridges).

The floodplains have been formed either by the accumulation of alluvial material deposited by streams during times of flood or by soil and saprolite material being deposited over the gully floor during a mudsliding mass movement event or both. Although some of the largest 'gullies' may technically be classified as small valleys, the term 'gully' was applied to all for consistency. Gully-floor channels are found where ephemeral to small permanent streams flow through narrow concave channels which usually occur between the bases of two relatively short side-slopes associated with spur ridges. The channels are often sloping. Where small but permanent streams flow, very narrow flat areas directly adjacent to the stream channel may qualify as gully-floor channels unless the foot-slope extends to the stream channel. The ephemeral and small permanent streams are tributaries to the larger streams and together they comprise the drainage network in the landscape.

Mudslide features

Mudslide features are landforms that presumably formed due to mudsliding mass movement processes (Chapter 3, section 3.3.4.1). The mudslide features component was subdivided into two land elements: (1) mudslide feature mounds (MFm) and (2) mudslide feature benches (MFb) (Figure 4.9). The mudslide feature mounds (Figure 4.12a) are small to relatively large, rounded (convex contour and profile shape), and discrete mounds, which tend to occur on side-slopes of gentle slope (roughly 4-7°). These mounds possibly originated as 'blocks' of hill-slope that broke away from the rest of the slope in mudslide source areas and were transported amongst the loose material down the path of the flow to be deposited in a lower part of the landscape (V. Moon, 11 September, 2002, personal communication). Mudslide feature benches (Figure 4.12b) are flat (about 0-3°), relatively small benches which sit within many side-slopes (usually within middle back-slopes). The slope above the bench tends to be fairly steep. It is possible that the benches formed within the source areas of mudslides.

Figure 4.12. (a) Mudslide feature mounds situated on a gently sloping side-slope and (b) a mudslide feature bench situated within a side-slope in southern Mahurangi Forest.

4.3.2.2 The refined landscape frameworks

The modified initial landscape framework was refined to create a more practical and functional landscape framework for each soil-landscape model (section 4.2.4.3). Rather than standing alone, the refined landscape frameworks encompass the land elements and sub-elements of the modified initial landscape framework and as such encapsulate but do not explicitly express the detail of the modified initial framework.

Both refined landscape frameworks consist of a broad, three-tiered hierarchical subdivision of the landscape with the land system at the broadest level of the hierarchy. At the second level, the land system was subdivided into three land zones: (1) Upper, (2) Middle, and (3) Lower. The Middle zone in each plot was further subdivided into two land sub-zones which represent the third level of the hierarchy.

In this study, the term 'land zone' is used primarily to refer to broad landscape positions rather than specific geomorphic features. Therefore, land zones comprise an amalgam of land elements and sub-elements which usually occur adjacent to one another in a similar part (zone) of the landscape. However, three land elements, RSd, MFm, and MFb, were assigned to different zones based on their soil drainage conditions rather than on their positions in the landscape because the soil drainage classes contained within these elements were more a reflection of landform morphology than landscape position. In other studies (e.g. King, 1970), the term 'land zone' has been used to represent a broader, climate-related, landscape subdivision than the land system. Land sub-zones represent the subdivision of a zone according to a specific geomorphic factor/terrain attribute (e.g. slope-shape or relative elevation), and have the purpose of attaining more clearly defined soil-landscape relationships. The two refined landscape frameworks differ at the sub-zone level of the hierarchy because a different geomorphic factor/terrain attribute was used to define the sub-zones of each framework (section 4.2.4.3). The nature, spatial extent, and position of the zones and sub-zones are essentially defined by their constituent elements and sub-elements (discussed below).

Representation of the refined landscape frameworks

The land zones and sub-zones described below, their relative positions in the landscape, and their relationships to the land elements and sub-elements are illustrated using an idealised block diagram (Figure 4.13).

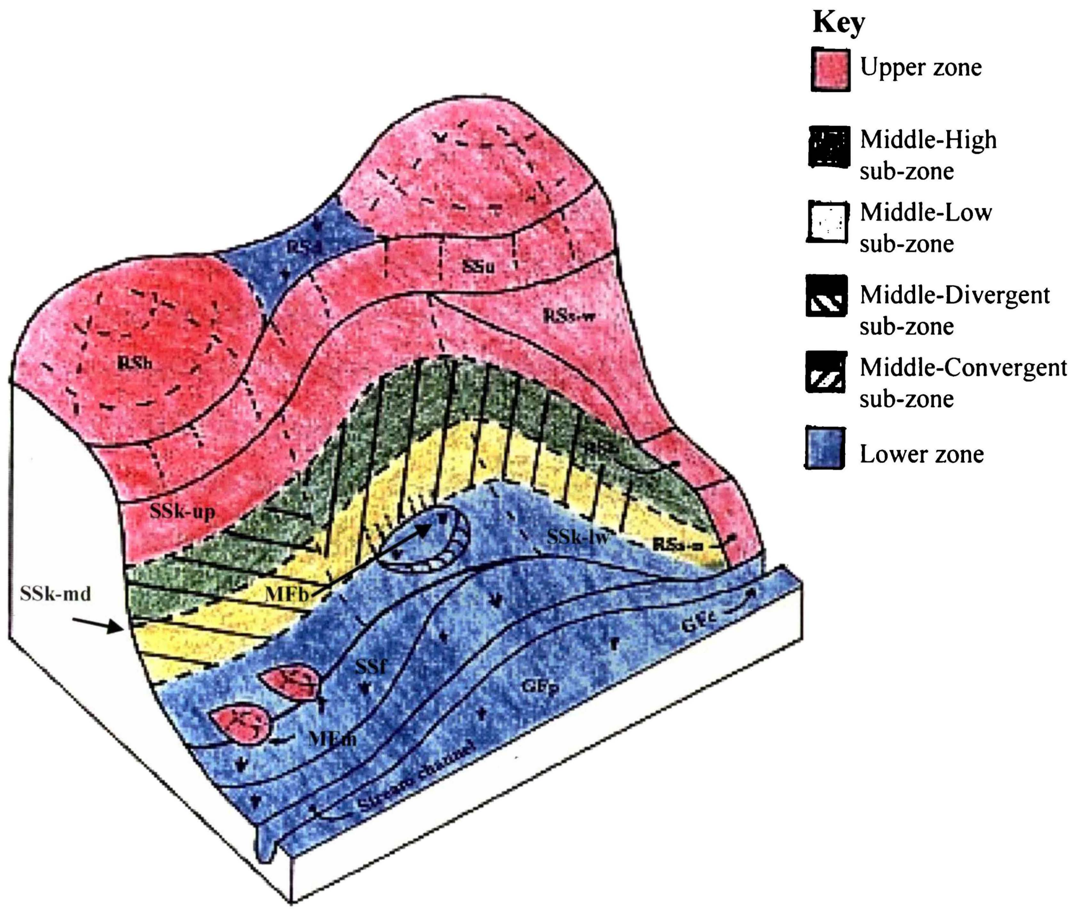


Figure 4.13. An idealised block diagram illustrating the nature and position of the land zones and sub-zones within both plots. Key: RSs-n = narrow ridge summit slopes, RSs-w = wide ridge summit slopes, RSb = ridge summit bench, RSh = ridge summit hillock, RSd = ridge summit saddle, SSu = side-slope shoulder, SSk-up = upper side-slope back-slope, SSk-md = middle side-slope back-slope, SSk-lw = lower side-slope back-slope, SSf = side-slope foot-slope, GFp = gully floor floodplain, GFc = gully floor channel, MFm = mudslide feature mound, MFb = mudslide feature bench.

Upper zone

The Upper zone encompasses the more elevated 'upper' parts of the landscape and those elements (e.g. MFm) that may occur in lower parts of the landscape but protrude above their immediate surroundings (i.e. that have high relative elevation). Eight elements or sub-elements spanning three land components are included within the Upper zone: (1) RSh, (2) RSb, (3) RSs-n, (4) RSs-w, (5) RSh, (6) SSu, (7) SSk-up, and (8) MFm (Figure 4.13). That is, most ridge summits, the upper parts of side-slopes (shoulders and upper back-slopes), and mudslide feature mounds (where ever they occur in the landscape) comprise the Upper zone. The elevated position or divergent morphology (or both) of the elements and sub-elements of the Upper zone appears to result in the relatively rapid drainage of water from this zone.

Lower zone

The less elevated 'lower' portions of the landscape and those elements (e.g. MFb) that may occur in higher landscape positions but lie beneath their immediate surroundings (i.e. have low relative elevation) are encompassed within the Lower zone. More specifically, six elements or sub-elements of four land components are included: (1) SSk-lw, (2) SSf, (3) GFc, (4) GFp, (5) MFb, and (6) RSd (Figure 4.13). In effect, the Lower zone includes the lower parts of side-slopes (lower back-slopes and foot-slopes), all gully floors, mudslide feature benches (where ever they occur in the landscape), and the saddles that occur on some ridge summits. Water seems to accumulate and persist (the water table is often near to the surface) in the elements and sub-elements of the Lower zone due to their less elevated positions or convergent morphology, or both. The convergent morphology of the mudslide feature benches and ridge summit saddles appears to 'trap' water at comparatively high landscape positions and often results in a perched water table.

Middle zone

The Middle zone encompasses the portion of the landscape at intermediate elevations, situated between the Upper and Lower zones. A single sub-element, representing the central 50% of all side-slope back-slopes (i.e. middle side-slope back-slopes, SSk-md), is included in the Middle zone (Figure 4.13). Although the Middle zone contains only one sub-element it represents a substantial proportion of the land area at the study site because the landscape is hilly and the back-slopes are long in relation to summit or gully floor widths. The Middle zone encompasses two sub-zones, based on relative elevation class, in the pre-harvested plot (Figure 4.13): Middle-High (Middle-H) and Middle-L (Middle-L), and two sub-zones, based on slope-shape class, in the post-harvested plot (Figure 4.13): Middle-Convergent (Middle-C) and Middle-Divergent (Middle-D). Overall, it appears that the rate at which water drains from the Middle zone is intermediate with respect to that in the Upper and Lower zones, probably because it receives water from the Upper zone but also drains water to the Lower zone. It has been recognised that within the Middle zone (middle back-slopes) water is probably moving down-slope from high to low positions in addition to across-slope from divergent to convergent positions (Pennock *et al.*, 1987) (Figure 4.14).

Consequently, the Middle-H back-slopes (above 47% relative elevation) ought to be drier than the Middle-L back-slopes (47% relative elevation or below) in the pre-harvested plot and the Middle-D back-slopes (generally convex) should be drier than the Middle-C back-slopes (generally concave) in the post-harvested plot. Although the sub-zones of the two refined frameworks are defined differently they are generally analogous in terms of expected soil drainage: Middle-H is roughly equivalent to Middle-D whereas Middle-L is roughly equivalent to Middle-C.

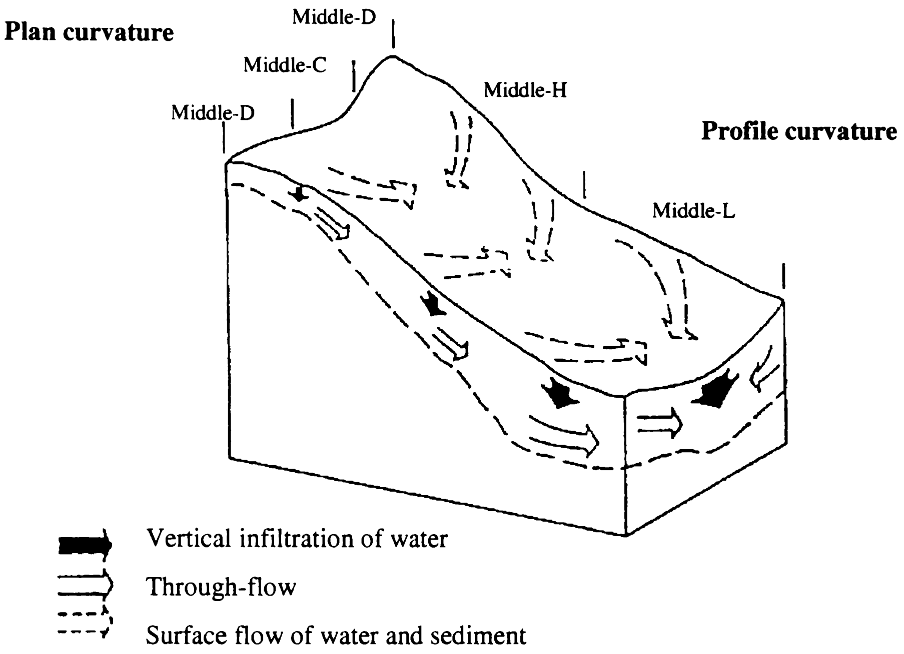


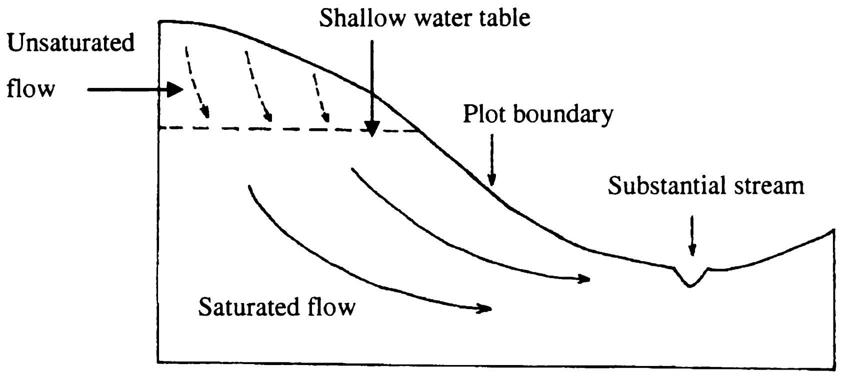
Figure 4.14. Pattern of water movement (infiltration, surface flow, and through-flow) commonly found in complex (divergent and convergent) side-slopes (adapted from Pennock *et al.*, 1987 after Hall and Olsen, 1991, p. 15).

4.3.2.3 Definition of the landscape units

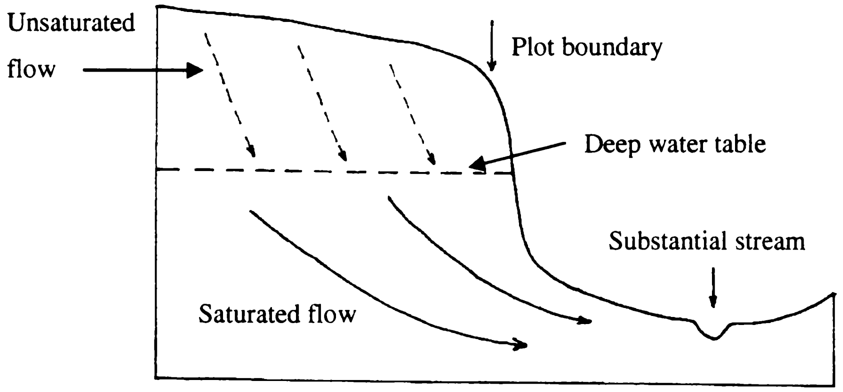
The landscape units of the soil-landscape models were defined to be the final versions of the zones and sub-zones of each framework (Figure 4.13). Because the land sub-zones of the pre-harvested plot are defined differently from those of the post-harvested plot, the landscape units of the two frameworks are slightly different. The four landscape units of the pre-harvested framework are (1) Upper, (2) Middle-H, (3) Middle-L, and (4) Lower, whereas the four landscape units of the post-harvested framework are defined as (1) Upper, (2) Middle-D, (3) Middle-C, and (4) Lower.

4.3.2.4 Differences in the landscape hydrology of the plots

Although both plots contain similar sub-catchments with similar assemblages of land elements and sub-elements, the need for two different refined landscape frameworks (one for each plot) has highlighted a naturally occurring difference in the landscape structure of the plots. The difference in landscape structures of the pre- and post-harvested plots (Figure 4.15) appears to have resulted in the plots having different landscape hydrologies. Moreover, the difference in landscape hydrology is probably responsible for the greater abundance of Dry soils in the post-harvested plot (section 4.3.1.4).



Pre-harvested sub-catchment



Post-harvested sub-catchment

Figure 4.15. Landscape structure and inferred hydrology of the pre- and post-harvested plots (sub-catchments).

The stream in the post-harvested sub-catchment remained relatively elevated with a fairly shallow gradient along the length of the plot. Just outside the plot boundary the stream gradient increased sharply where it began to cascade down a long and very steep slope to join a more substantial stream (the headwaters of the Mahurangi River) running through the much larger gully below. In essence, the post-harvested sub-catchment is a ‘hanging’ gully meaning that the stream (and gully floor along which it flows) is 'suspended' above the larger stream in the much deeper gully. The stream in the pre-harvested sub-catchment has a steeper gradient than the stream in the post-harvested sub-catchment (within the confines of the plot boundary) and consequently there is a greater reduction in stream elevation within the pre-harvested plot than there is within the post-harvested. Outside plot boundaries, the stream draining the pre-harvested sub-catchment descends more gradually than the stream draining the post-harvested sub-catchment. It is speculated that the hanging nature of the post-harvested sub-catchment has resulted in strong hydraulic gradients and a relatively deep water table across the entire plot. These conditions may have, in turn, lead to all landscape units draining more rapidly than the equivalent units in the pre-harvested sub-catchment where the hydraulic gradients are likely to be weaker and the water table shallower. Although the upper parts (Upper and Middle-H landscape units) of the pre-harvested sub-catchment are likely to be relatively free draining, the lower parts (Middle-L and Lower landscape units) are probably wetter than the equivalent units in the post-harvested sub-catchment. Therefore, landscape position – as expressed by relative elevation class – is a more important determinant and indicator of wetness differences within the pre-harvested plot than it is in the post-harvested plot. Slope-shape is instead a relatively more useful indicator of wetness differences within the Middle zone of the post-harvested plot due to the generally weaker association between landscape position and wetness in that plot. Nevertheless, landscape position is probably the overarching determinant of wetness in the post-harvested plot (i.e. the Lower landscape unit is likely to be wetter than the Upper unit).

4.3.3 Characterisation of the soil-landscape models

Each of the soil-landscape models developed in this study represents a set of soil-landscape relationships derived from the integration of the landscape frameworks (embodied by the landscape units) and the identified soil drainage classes (ultimately represented by the broad soil drainage classes). The soil-landscape models are characterised via the examination of the soil-landscape relationships comprising each model. The soil-landscape units, which embody the soil-landscape relationships, are also defined.

4.3.3.1 The soil-landscape relationships

The soil-landscape relationships are examined at three levels. Firstly, the relationships between the modified drainage classes and the landscape units are described. These are the primary, though not the functional, relationships comprising the soil-landscape models. Secondly, at a more detailed level, the relationships between the NZSC subgroups and the landscape units (in addition to the land elements and sub-elements) are considered. Finally, the soil-landscape relationships are summarised by discussing the relationships between the broad drainage classes and the landscape units (the functional relationships of the models).

Relationships between the modified soil drainage classes and the landscape units

All landscape units in both models contain several (three to four) modified soil drainage classes. Nevertheless, some general relationships exist. The relationships between the modified soil drainage classes and the landscape units of the pre-harvested model are presented in Figure 4.16.

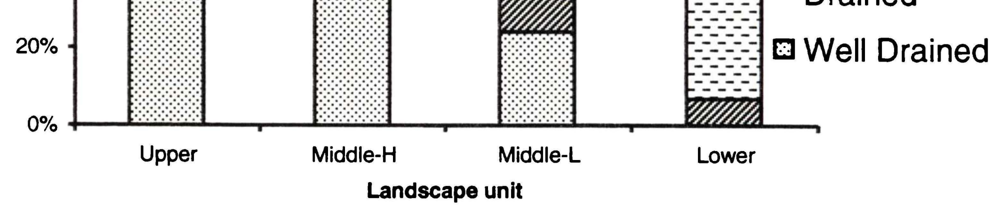


Figure 4.16. Abundance of modified soil drainage classes in the landscape units of the pre-harvested model.

The more elevated Upper and Middle-H landscape units are dominated by the Well and Imperfectly Drained soils which, in combination, account for 87% of observations in the Upper unit and 77% of those in the Middle-H unit. In both the Upper and Middle-H units, the Well Drained class is the most common class whereas the Imperfectly Drained class is the second most common.

Consequently, the Somewhat Poorly and Poorly Drained soils were relatively uncommon in the Upper and Middle-H landscape units with the Poorly Drained soils being completely absent from the Upper unit. In contrast, the less elevated Middle-L and Lower landscape units are dominated by the Somewhat Poorly and Poorly Drained soils which together account for 64% of observations in the Middle-L unit and 93% those in the Lower unit. The Poorly Drained soils remained relatively uncommon in the Middle-L unit, accounting for only 14% of observations whereas the Well Drained class was the second most common class behind the Somewhat Poorly Drained soils. However, the Poorly Drained class accounted for the majority (60%) of observations in the Lower landscape unit. Furthermore, the Well Drained soils were absent from the Lower Unit.

The relationships between the modified soil drainage classes and the landscape units of the post-harvested model (Figure 4.17) are generally similar to those of the pre-harvested model.

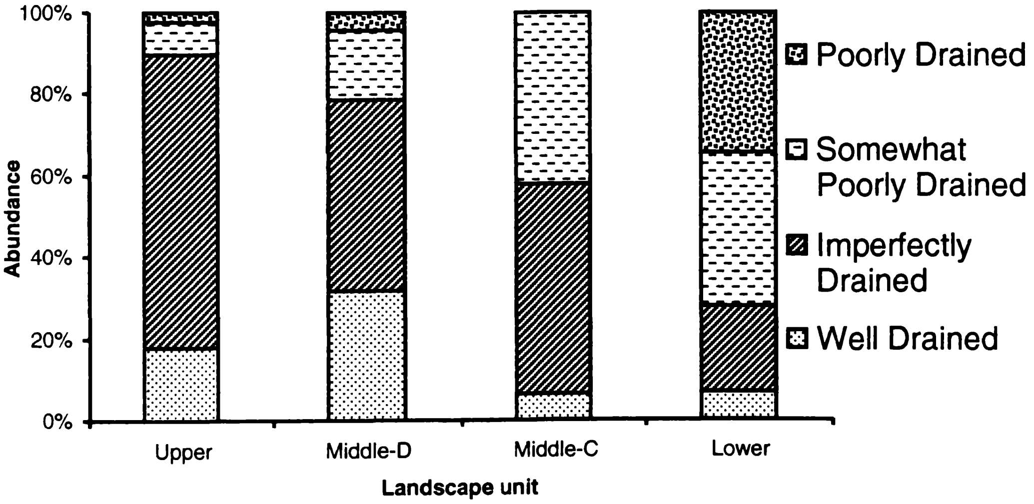


Figure 4.17. Abundance of modified soil drainage classes in the landscape units of the post-harvested model.

The main point of difference between the soil-landscape relationships of the two models is that the Well and Imperfectly Drained soils dominate not only the two drier landscape units (Upper and Middle-D) but also the potentially wetter Middle-C unit. Together, the Well and Imperfectly Drained classes account for 90% of observations in the Upper landscape unit and 79% of those in the Middle-D unit. These soils are slightly less common in the Middle-C unit but still sufficiently common to account for the majority of observations (58%). Moreover, the Imperfectly Drained class is more common than the Well Drained class in all landscape units and is the most common class in all landscape units apart from the Lower unit (c.f. the pre-harvested model). The dominance of the Well and Imperfectly Drained soils in the Middle-C unit is probably attributable to the generally drier nature of the landscape in the post-harvested plot (section 4.3.2.4). The Somewhat Poorly and Poorly Drained soils are dominant in the Lower landscape unit where together they account for 72% of observations (with each accounting for a similar proportion). The Somewhat Poorly Drained class is the second most common class in the Middle-C unit whereas the Poorly Drained soils are absent from that unit. Also in contrast to the pre-harvested model, the Well Drained soils are more common in the Middle-D landscape unit than they are in the Upper unit. It is possible that the some of the Well Drained soils of the Upper landscape unit were compacted by the trafficking of harvesting machinery along ridge summits and as a result developed redox segregations in their upper profiles making them Imperfectly Drained soils. Consequently, the Well Drained soils became less common in the Upper landscape unit and relatively more common in the Middle-D unit. The presence of some Poorly Drained soils in the Upper landscape unit further suggests that compaction during harvesting has impeded the drainage of some soil profiles. The presence of some Well Drained soils in the Lower landscape unit and the absence of Poorly Drained soils from the Middle-C unit may be due to the generally drier nature of the post-harvested plot landscape.

Relationships between the NZSC subgroups and the landscape units

A greater understanding of the soil-landscape relationships can be gained by examining the relationships between the NZSC subgroups and the landscape units. The subgroups that dominate the modified drainage classes (UYT, UYM1, UYM2, and UPT Soils) are ubiquitous across the landscape with only their abundances differing among the landscape units of both models (Figures 4.18 and 4.19). However, the occurrence of the less common subgroups in the landscape tends to reveal more about the influence of topography on pedogenesis in the study area.

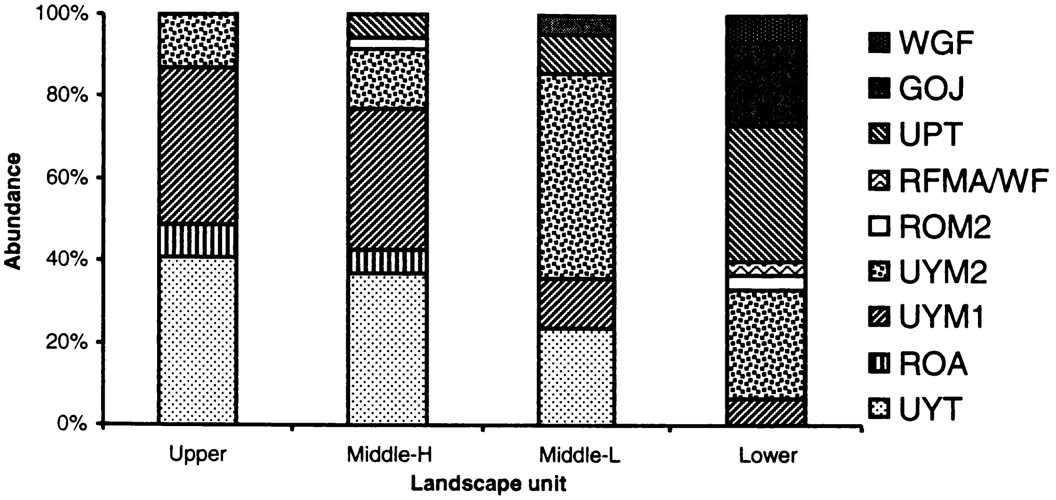


Figure 4.18. Abundance of NZSC subgroups in the landscape units of the pre-harvested model.

In the pre-harvested model (Figure 4.18) the UYM1 and UYM2 Soils occur in all landscape units and the UYT and UPT Soils occur in three of the four units. The UYT Soils are absent from the Lower landscape unit whereas the UPT Soils do not occur in the Upper unit. The GOJ Soils occur only in the Middle-L and Lower landscape units where the water table is elevated for durations sufficient to impart a gley profile form with reductimorphic horizons that extent to the base of the B horizon. In the Middle-H unit the UPT subgroup is the sole representative of the Poorly Drained soils because in these more elevated positions the water table is not sufficiently high to produce a gley profile form unless it is perched (as is the case with the UPT Soils). Within the Lower unit, the UPT Soils are most common in the flattish MFb and SSf elements where water tends to pond. Moreover, the MFb element is dominated by the UPT subgroup in the pre-harvested plot. The ROA subgroup is restricted to the more elevated landscape units (Upper and Middle-H) and is most common in the Upper unit. More specifically, the ROA Soils are most common on the RSs-n sub-element where the narrow nature of the landform appears to be indicative of relatively recent erosion. This suggests that the ROA Soils are associated with the more eroded, relatively steep, and convex parts of the Upper and Middle-H units where their profiles remain free-draining and weakly developed. The ROM2 Soils are present in both the Middle-H and Lower landscape units. Within the Lower unit they are most common on the steeper parts of the SSk-lw sub-element where longer durations of saturation (producing a mottled profile form) and erosion (maintaining weak profile development) coincide. The RFMA/WF Soils occur exclusively on the GF component within the Lower landscape unit because these soils are defined largely on the fluvial nature of the sediments from which they are formed. The fluvial sediments are deposited adjacent to the streams in the study area. Consequently, the RFMA/WF Soils occur adjacent to the streams on gully floors. Also restricted to the Lower landscape unit are the WGF Soils. However, these soils occur only on the relatively steep and very wet parts of the SSk-lw sub-element. The extreme wetness of the lower slopes (probably indicative of seepage faces) on which the WGF Soils occur has lead to the upper soil horizons being fluid and gleyed. The steepness of the slopes, and hence their instability, has probably resulted in the very weak development of these soils.

The relationships between the NZSC subgroups and the landscape units of the post-harvested model (Figure 4.19) are generally similar to those of the pre-harvested model. However, there are a few notable differences which are discussed below.

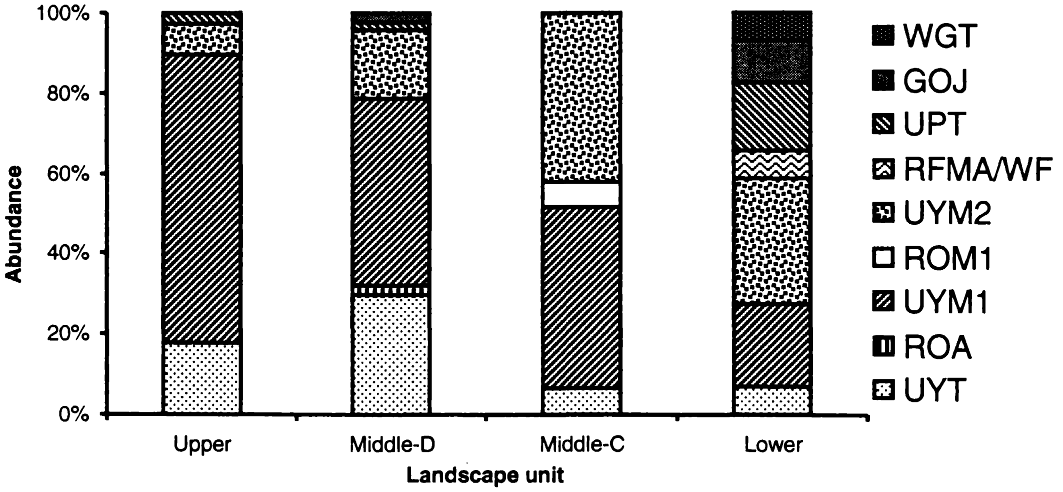


Figure 4.19. Abundance of NZSC subgroups in the landscape units of the post-harvested model.

The UYT, UYM1, and UYM2 Soils occur in all landscape units whereas the UPT Soils occur only in three of the four units (they are absent from the Middle-C unit). The few ROA Soils that occur are restricted to the steep and divergent parts of the SSk-md sub-element within the Middle-D unit. The steep and divergent nature of the slopes is responsible for the weakly developed and free-draining nature of the ROA profiles. ROM1 Soils occur (instead of the ROM2 Soils found in the pre-harvested plot) exclusively within the Middle-C landscape unit where they occupy the relatively steep and convergent parts of the SSk-md sub-element. The steepness and convergence of water into these slopes has resulted in the formation of the mottled profile form and weakly developed profile characteristic of the ROM Soils. The RFMA/WF Soils occur only on the GF component of the Lower landscape unit as they do in the pre-harvested model. The WGT Soils also occur exclusively on the GF component of the Lower unit. In contrast to the WGF Soils of the pre-harvested plot, the WGT Soils represent recent colluvial deposits that have been gleyed by the presence of the water table near to the surface and are very weakly developed due to the youthfulness of the deposits.

Relationships between the broad drainage classes and the landscape units

The soil-landscape relationships of both models can be effectively summarised by considering the relationships between the broad drainage classes and the landscape units (Figures 4.20 and 4.21).

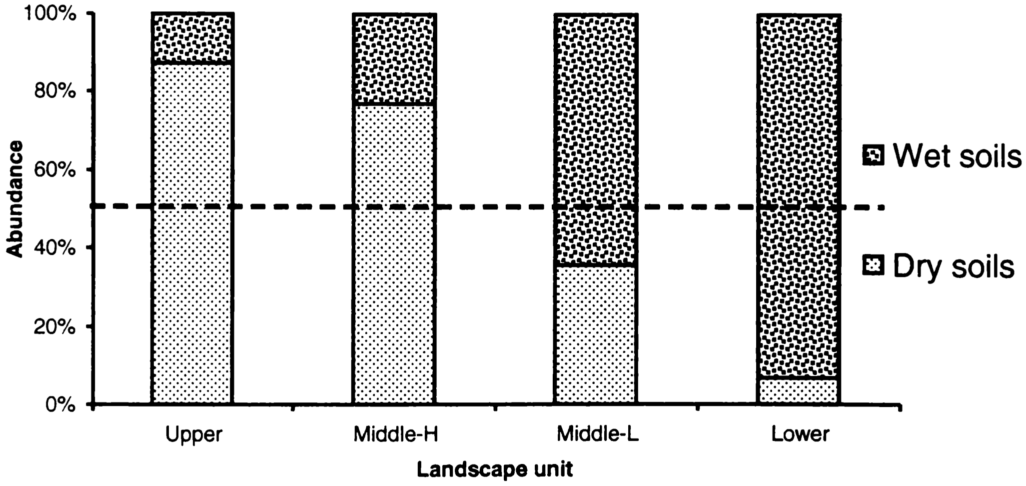


Figure 4.20. Abundance of broad soil drainage classes in the landscape units of the pre-harvested model. The dashed line indicates an abundance of 50% which represents the threshold used in the definition of the soil-landscape units (the class with an abundance > 50% is considered dominant).

In the pre-harvested model the Dry soils dominate the Upper and Middle-H landscape units whereas the Wet soils dominate the Middle-L and Lower units (Figure 4.20). The dominance of the Dry soils in the more elevated landscape units is probably due to a combination of factors: the absence of a water table near to the solum, few upslope areas contributing to the inward flow of water, and the often divergent landform morphology which favours more rapid water runoff and drainage. Therefore, the Upper and Middle-H landscape units are probably saturated for much shorter durations than are the less elevated units. Figure 4.20 also shows that there is a clear trend in the soil-landscape relationships of the pre-harvested model. The Dry soils become relatively less common as one moves from the upper parts of the landscape (e.g. ridge summits) to the lower parts (e.g. gully floors) whereas the Wet soils become relatively more common. Note that the abrupt decrease in the abundance of Dry soils and the corresponding increase in the abundance of the Wet soils between the Middle-H and Middle-L landscape units coincides with the change in dominance (surpassing the 50% threshold) from the Dry to the Wet soils and, in physical terms, with the 47% relative elevation threshold (section 4.2.4.3 and Figure 4.13).

The relationships between the landscape units and the broad drainage classes of the post-harvested model (Figure 4.21) are similar to those of the pre-harvested model but with several key exceptions. Firstly, the Dry soils dominate the Middle-C unit whereas the equivalent unit in the pre-harvested plot (Middle-L) was dominated by the Wet soils. Secondly, the Dry soils are more common in the Lower unit than is the case for the Lower unit of the pre-harvested model. Therefore, relationships between the broad drainage classes and the landscape units are fractionally weaker in the post-harvest plot than in the pre-harvested. However, the weaker relationships are probably due to the generally drier nature of the landscape in the post-harvested plot and are not likely to be due to forest harvesting.

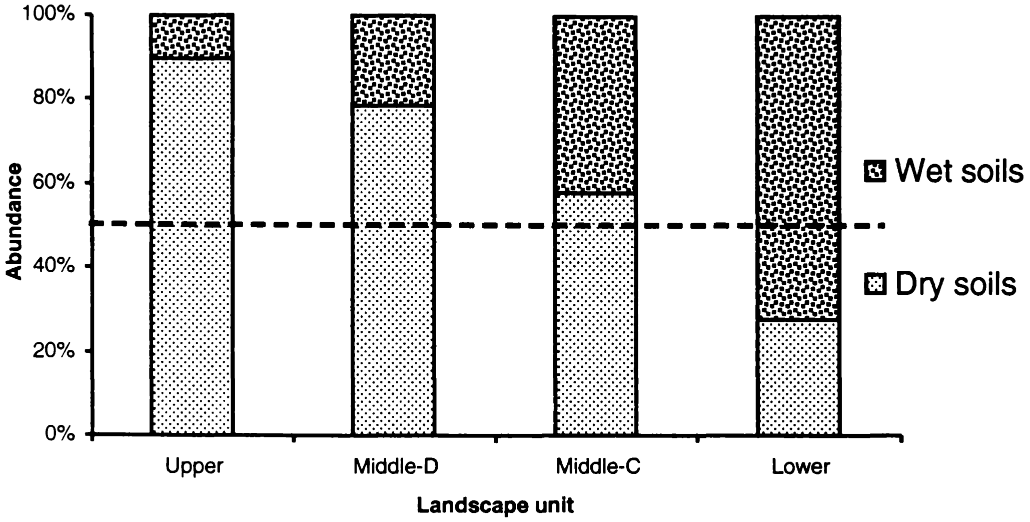


Figure 4.21. Abundance of broad soil drainage classes in the landscape units of the post-harvested model. The dashed line indicates an abundance of 50% which represents the threshold used in the definition of the soil-landscape units (the class with an abundance > 50% is considered dominant).

The general trend of the Dry soils becoming less common in the lower parts of the landscape is also evident in the post-harvested model. However, the difference in the dominance of the Dry soils between the Middle-D and Middle-C units is not due to a difference in landscape position (relative elevation) but rather it is the result of a difference in slope-shape. The Dry soils are more common in the Middle-D unit than in the Middle-C unit because water tends to flow away from divergent slopes and into convergent slopes. Therefore, convergent slopes are probably saturated for longer periods of time than are the divergent slopes.

4.3.3.2 Definition of the soil-landscape units

The soil-landscape relationships comprising the two models are encapsulated and expressed in the form of soil-landscape units. That is, the soil-landscape units represent the integration of the landscape units and the broad soil drainage classes for the purpose of predicting those drainage classes across the landscape. The soil-landscape units were defined on the basis of the dominant broad drainage class in each landscape unit. Thus, two soil-landscape units were defined in each model: Dry and Wet units. As their names suggest, the Dry soil-landscape unit is dominated by Dry soils whereas the Wet unit is predominantly comprised of Wet soils.

In the pre-harvested model the Dry soil-landscape unit includes the Upper and Middle-H landscape units because both contain more than 50% Dry soils as shown in Figure 4.20. The remaining two landscape units (Middle-L and Lower) are assigned to the Wet soil-landscape unit because over 50% of the observations in both units are Wet soils (Figure 4.20). In contrast, the Upper, Middle-D, and Middle-C landscape units comprise the Dry soil-landscape unit in the post-harvested model because all three were dominated by Dry soils (Figure 4.21). Consequently, the Wet soil-landscape unit in the post-harvested model includes only the Lower landscape unit. The composition of the soil-landscape units differs among the models because of the natural difference in the landscape hydrology of the plots (section 4.3.2.4) rather than because of any harvesting effects.

The soil-landscape units are assumed to be uniform in terms of soil drainage for the purposes of applying the models and evaluating (validating) their performance. However, the soil-landscape units of both models are complexes consisting of two broad drainage classes, one dominant, the other subdominant (inclusions), as show in Figure 4.22.

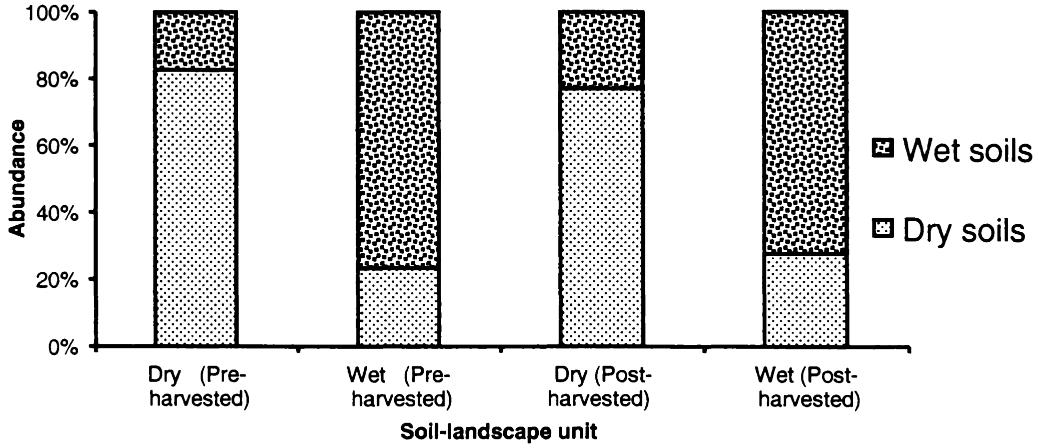


Figure 4.22. Abundance of broad soil drainage classes in the soil-landscape units of both models.

All soil-landscape units were reasonably pure with no unit containing more than 28% inclusions. The purity of the Dry soil-landscape units was similar for both models (around 80% pure). The Wet units were a little less pure than the Dry but the purity was similar for both models (about 74% pure).

4.3.4 Application of the soil-landscape models

Both soil-landscape models were applied across their respective plots, meaning that broad soil drainage class was predicted at all data points (development and validation). The models are presented here in the form of maps (one for each model) showing the spatial distribution of the broad drainage classes predicted in each plot (Figure 4.23).

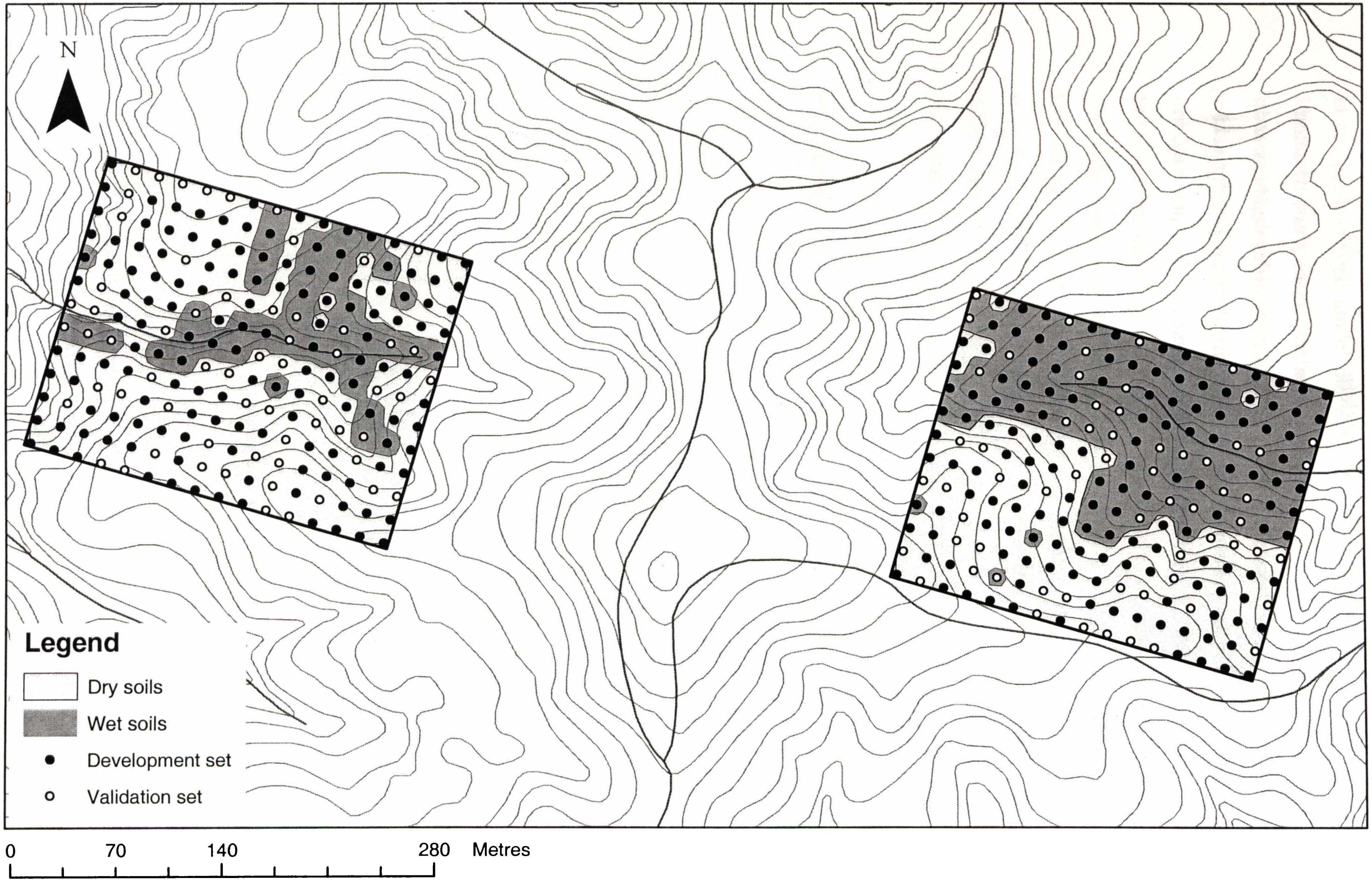


Figure 4.23. Predicted spatial distribution of broad soil drainage classes in the pre- and post-harvested plots.

Figure 4.23 shows that in the pre-harvested plot the Dry soils are generally predicted to occur in the more elevated parts of the landscape (Upper and Middle-H landscape units) and that the Wet soils occupy the lower parts and extend up to the middle of the side-slopes (Lower and Middle-L landscape units). In contrast, the Wet soils are essentially restricted to the lower landscape positions (Lower landscape unit) in the post-harvested plot (Figure 4.23).

4.3.5 Evaluation of the soil-landscape models

Both soil-landscape models were found to perform well. The pre-harvested model correctly predicted broad drainage class at 82% of the validation points whereas the post-harvested model made correct predictions at 85% of the validation points. The performance of the models is particularly good given that the soil-landscape units of both models are known to contain up to 28% inclusions. Although forest harvesting may have altered the abundance of some of the modified drainage classes (e.g. the Well Drained soils) in the post-harvested plot, the performance of the post-harvested model was not adversely affected by the forest harvesting activities.

Given that the landscape hydrology of the two plots is slightly different, the key factor in the success of both models is probably that each was developed to suit the specific soil-landscape relationships of the plot in which it was to be applied. This result suggests that the stratification of a land system on the basis of important differences in landscape hydrology in the early stages of landscape framework development could be very useful when developing soil-landscape models to be applied over much larger areas than the 5-ha plots used in this study. Any landscape hydrology-related differences in the soil-landscape relationships could then be accounted for in the soil-landscape model or, if necessary, separate models could be developed for the hydrologically distinct areas.

4.4 Summary and conclusions

The soils of southern Mahurangi Forest differ predominantly in terms of soil drainage condition. Therefore, the soil continuum within the forest was found to be most effectively partitioned using soil drainage classes. The New Zealand soil drainage criteria were modified to partition better the variation in soil profile hydromorphology with the key modification being the subdivision of the existing imperfectly drained class into two new classes (Imperfectly Drained and Somewhat Poorly Drained). Soil compaction caused by forest harvesting activities may be responsible for the lower abundance of Well Drained soils and, to a certain extent, the greater abundance of the Imperfectly Drained soils in the post-harvested plot.

A natural difference in the landscape hydrology of the plots resulted in a greater abundance of Dry soils in the post-harvested plot and the development of a separate landscape framework and model for each plot. The geomorphic factor most useful as a determinant and indicator of soil wetness in both plots is landscape position (e.g. Upper versus Lower landscape units). However, slope-shape was found to be relatively more useful within the Middle zone of the post-harvested plot.

In the pre-harvested model, the more elevated landscape positions (Upper and Middle-H landscape units) are dominated by the Dry soils whereas the lower landscape positions (Middle-L and Lower units) were dominated by the Wet soils. In the post-harvested model, all landscape units except the Lower unit are dominated by the Dry soils. However, the Wet soils were more common in the Middle-C unit than in the Middle-D unit. The most common NZSC subgroups (UYT, UYM1, UYM2, and UPT Soils) were ubiquitous across the landscape with only their abundances differing among the landscape units of both models. The less common subgroups tended to occur in the more extreme land elements or sub-elements (e.g. very steep or very wet, or both). The overall trend in both plots is for the Dry soils to become less common as one moves from the upper parts of the landscape (e.g. ridge summits) to the lower parts (e.g. gully floors) and from the divergent parts to the convergent parts (especially in the post-harvested plot).

Forest harvesting may have altered the soil-landscape relationships slightly by reducing the abundance of Well Drained soils in the more elevated landscape units. However, most differences are probably attributable to the naturally drier nature of the post-harvested landscape. Thus, it is concluded that forest harvesting did not substantially alter or weaken the relationships between the soil drainage classes and the landscape units.

The predictive performance of the models was good with both correctly predicting broad soil drainage class at >80% of the validation points. Therefore, it is concluded that forest harvesting had no adverse impact on the performance of the qualitative soil-landscape models. This result indicates that the development of accurate qualitative soil-landscape models in southern Mahurangi Forest does not require the stratification of the landscape by land management status (i.e. into pre- and post-harvested areas). The results also suggest that differences in landscape hydrology should be explicitly investigated in the preliminary stages of the soil-landscape modelling process.

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CHAPTER FIVE

Impacts of forest harvesting on soil properties and their relationship to soil drainage classes and the landscape

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5.1 Introduction

The movement of New Zealand's forestry industry towards sustainable and site-specific forest management has created new and specific demands for forest soil information. Quantitative, precise, and detailed information on the magnitude and variability of certain target soil properties (i.e. key soil indicators of sustainable forestry), in addition to accurate information regarding the spatial distribution of locally significant soil classes (e.g. drainage classes), is essential for assessing and monitoring forest site quality and for implementing site-specific forest management programmes (Payn and Thwaites, 1998; Turner *et al.*, 1999; Payn *et al.*, 1999, 2000; Fox, 2000; Shaw and Carter, 2002). There is also a commercial desire for this soil information to be collected in a cost-effective manner and presented in easily accessible, flexible formats (Payn and Thwaites, 1998).

Most existing soil property information relating to New Zealand's forest estates is inadequate, being generally too sparse for the comprehensive assessment of forest site quality and the implementation of site-specific forest management (Payn and Thwaites, 1998; Payn *et al.*, 1999, 2000). Therefore, the required target soil property information must be collected before sustainable and site-specific forest management can be achieved (Payn *et al.*, 1999).

The impacts of plantation forest harvesting and related disturbances on the magnitude of soil properties have been widely investigated both within New Zealand and internationally (e.g. Krzic *et al.*, 2001; McNabb *et al.*, 2001; Block *et al.*, 2002; Parfitt *et al.*, 2002). These studies commonly report significant changes to soil property values after harvesting (e.g. Schmidt *et al.*, 1996; Lacey and Ryan, 2000; Startsev and McNabb, 2000; Simard *et al.*, 2001). The effects of afforestation on soil properties have also been well studied in New Zealand by comparing soils under *Pinus radiata* forest with those under pasture (e.g. Parfitt *et al.*, 1997; Davis, 2001; Davis and Condron, 2002; Groenendijk *et al.*, 2002; Ross *et al.*, 2002). However, few studies have examined the affects of forest harvesting on the variance of soil properties (e.g. Courtin *et al.*, 1983; Shaw and Carter, 2002), particularly within New Zealand's plantation forests. Furthermore, little is known about the impacts of forest harvesting on the predictive relationships that may be used by various approaches to the spatial prediction of target soil properties (e.g. quantitative soil-landscape modelling). The substantial impacts that plantation forest harvesting activities can have on soil properties may alter or weaken these predictive relationships (Block *et al.*, 2002). Consequently, the predictive performance of quantitative soil-landscape modelling or other approaches to the spatial prediction of target soil properties (e.g. class-based) may be reduced after forest harvesting. Therefore, an understanding of the impacts of forest harvesting on these predictive relationships may facilitate the selection, development, and application of the technique most suited to the spatial prediction of target soil properties in plantation forest environments and may lead to improved interpretation of the predictive performance of the various techniques.

This chapter reports on a study conducted as part of a wider investigation into the impacts of hauler-based, clear-fell, forest harvesting on the performance of soil-landscape modelling as a tool for the spatial prediction of soil classes and target soil properties in a radiata pine forest. The research was conducted within southern Mahurangi Forest, an exotic, *Pinus radiata*-dominated plantation forest, situated on the Northland Peninsula, North Island, New Zealand. The objectives of this study were to determine the impacts of hauler-based, clear-fell, forest harvesting on (a) the magnitude and variance of the target soil properties and (b) the relationships between the target soil properties and the soil drainage classes, landscape units, soil-landscape units, and terrain attributes. The soil drainage classes, landscape units, and soil-landscape units were defined in Chapter 4.

For the purposes of this study, six target soil properties (key indicators of sustainable forestry) were measured: (1) topsoil pH, (2) available P, (3) available Mg, (4) available K, (5) macroporosity, and (6) total C. From this point on, the target soil properties shall collectively be referred to as 'the target properties'.

5.2 Methodology

The methods used to establish the sampling plots were described in the previous chapter (Chapter 4, section 4.2.2) and a comprehensive description of the study site location and environment was given in Chapter 3. The methods used in soil sampling and analysis, terrain analysis, and statistical analysis are described below.

5.2.1 Soil sampling and observation

The sampling and observation of the soil at each sample point in both plots occurred in three phases: (1) soil cores were taken for the analysis of macroporosity, (2) topsoil samples were taken for the analysis of the soil chemical properties, and (3) the key elements of the soil morphology were observed on auger samples (to allow the soils to be classified) at each point.

5.2.1.1 Sampling for macroporosity

The small-core method of macroporosity measurement (Drewry *et al.*, 2002) was used in this study. This method, originally developed for agricultural soils, allowed for large numbers of samples to be collected and analysed with relative ease (as opposed to the large cores used commonly for measuring macroporosity). The sampling ring comprised three separate metal rings that were bound together by waterproof plastic tape. All rings had a diameter of 4.8 cm. The central ring (used to contain the sample on which measurements were to be made) was 2 cm in height whereas the two spacer-rings above and below it were 1.5 cm in height. Therefore, the bound ring was 4.8 cm in diameter and 5 cm in height and the effective sampling depth range for macroporosity was 1.5-3.5 cm from the soil surface. The soil cores were taken in the field by placing a bound ring into a specially designed pogo sampler (the ring was held in place by four metal spikes) and then pushing the ring into the surface of the soil using the pogo sampler (Figure 5.1). The core was carefully removed from the soil (by moving the handle of the pogo sampler laterally), then from the pogo sampler before being bagged and packed to avoid breakage or disturbance of the core.

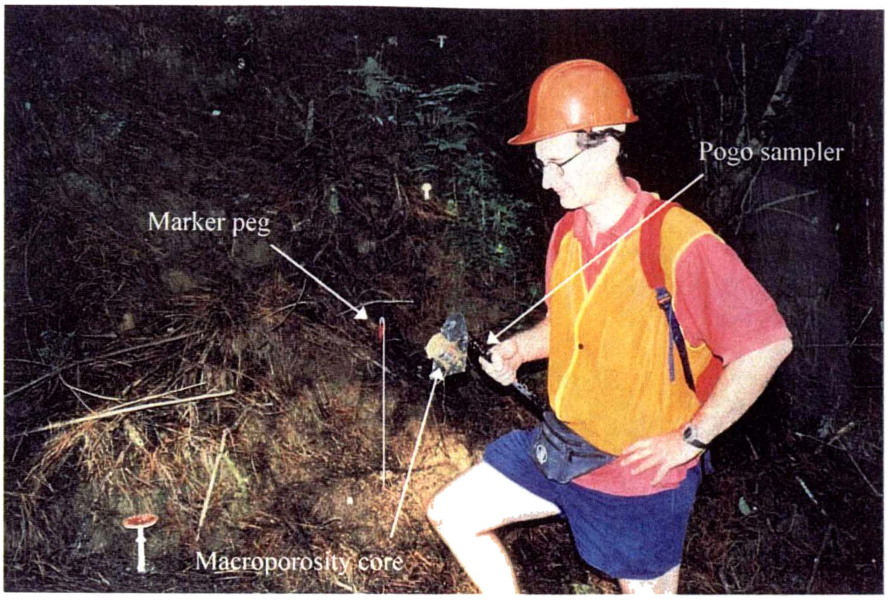

Figure 5.1. Sampling for macroporosity using a pogo sampler in the pre-harvested plot.

5.2.1.2 Sampling for soil chemistry

At each sample point, six topsoil (0-10 cm) sub-samples were taken using a pogo core sampler (Figure 5.2a), according to the layout described below, for the measurement of the soil chemical properties. The sub-samples were bulked in the field to give a single sample (Figure 5.2b). The reasons for bulking six sub-samples at one sample point were twofold: (1) it provided a more representative sample of the soil at the sample 'point' (defined below), and (2) it was necessary to gather sufficient soil material on which to perform the analyses.

Figure 5.2. (a) Collection and (b) bulking of topsoil samples for soil chemical analyses using a pogo sampler in the post-harvested plot.

5.2.1.3 Observation of soil morphology

Auger observations, to a depth of approximately 1.2 m, were made at each sample point in both plots in order to describe the soil morphology. Some key elements of the soil morphology were described and recorded to classify the soil into NZSC subgroups (Hewitt, 1998) and into modified soil drainage classes (Chapter 4, section 4.3.1.2). The key morphological elements described were depth to horizon boundaries, matrix colour, presence of redox mottles (redox segregations), presence of redox depletions, horizonation, solum thickness, and saprolite type (differentiated by colour). The descriptions of the auger samples were performed (as far as was practicable) in accordance with the standard soil description methodology of Milne *et al.* (1995) and horizon nomenclature of Clayden and Hewitt (1994).

5.2.1.4 Layout at individual sample points

An individual sample point is defined, for the purposes of this study, to be a circular area of approximately 2-m diameter with the marker peg, indicating the location of the sample point, at its centre. The first of the six sub-samples (making-up an individual bulked soil chemistry sample) was taken directly adjacent to the marker peg. Four further sub-samples were taken around the circumference of the sample point area (with a radius of approximately 1 m) at intervals of about 90 degrees. The sixth sub-sample was taken about 0.5 m from the marker peg in any direction. The auger observation was made at about 0.5 m from the marker peg also. The macroporosity sample was also taken at 0.5 m from the marker peg but at a point separate from the auger hole. The layout of an individual sample point is illustrated in Figure 5.3.

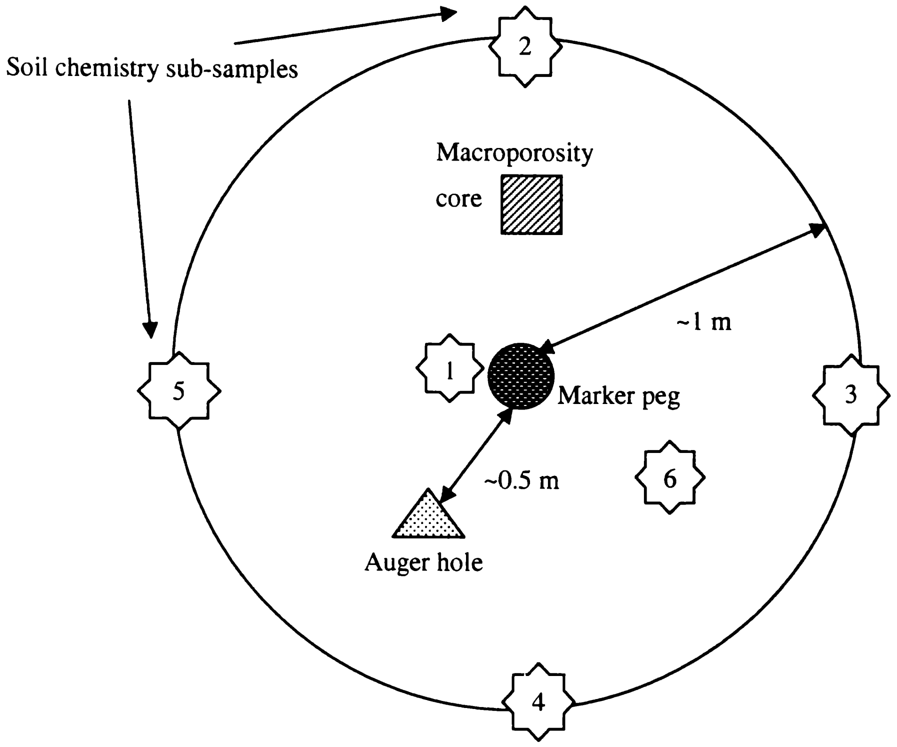

Figure 5.3. An idealised diagram showing the layout (plan view) of an individual sample point.

5.2.2 Soil analysis

The analytical methods used for the measurement of the soil chemical properties were standard techniques commonly used for the analysis of forest soils in New Zealand (or slightly modified). All soil chemical analyses were conducted on air-dried soil of the fine-earth fraction (less than 2 mm) with the exception of total C, which was measured on finely ground soil (less than 0.25 mm). Macroporosity was measured on intact soil cores using a small-core method developed for agricultural soils. Cores were stored for up to 48 hours in a cool room (at 4° C) before analysis. Particle density was also measured as a part of the macroporosity analysis.

5.2.2.1 Topsoil pH

The method used to measure topsoil pH in H_2O essentially follows method 2A of Blakemore *et al.* (1987). To 10 g of soil, 25 ml of distilled water was added. The slurry was mixed vigorously for 30 seconds using a high-speed stirrer and left to settle for 16 hours. The pH was then measured by placing the tip of the electrode fractionally below the surface of the soil settled at the bottom of the beaker.

5.2.2.2 Available P, K and Mg

The Bray-2 method of P and cation extraction (Ballard, 1974, 1978; Nicholson, 1984, 1989) was employed for the measurement available P, K, and Mg. The Bray solution (25 ml of 0.03 M NH_4F + 0.1 M HCl) was added to 2.5 g of soil. The sample was then shaken by hand for 1 minute before being centrifuged for 5 minutes at 3000 rpm. A 12 ml aliquot of supernatant was transferred to a test tube. The uncorrected concentrations of P, K, and Mg were measured by inductively coupled plasma-optical emission spectroscopy (ICP-OES). The use of ICP-OES meant that all three elements could be measured at the same time from a single aliquot. It also meant that it was not necessary to add lanthanum and aluminium which are normally added to prevent interference and other problems associated with the measurement of Mg using atomic absorption spectrophotometry. Therefore, the factor used in the correction of the Mg data was slightly different from that given by Nicholson (1989).

5.2.2.3 Macroporosity and particle density

The method of macroporosity measurement used (small core method) follows that of Drewry *et al.* (2002). The first step was to prepare the cores. After removing the plastic tape binding together the three rings of an individual core, the upper and lower spacer rings were carefully carved off using a very sharp, thin knife inserted between the spacer and the central rings. Cores that appeared too dry to safely carve were placed upright in a tray of water to increase the moisture content of the core. If any soil volume was lost from the central ring in the process of separating the spacer rings, the lost volume was estimated using clover seed. The outside of the central ring was wiped clean and the core was placed on a piece of filter paper (Whatman # 54, hardened, 5.5 cm circles) then positioned on a metal tray. Formalin (1%) was added to the trays containing the cores (to just below the top of the cores) to remove any soil fauna. The cores were left soaking in the formalin, in a fume hood, overnight. Over the following 24 hours, the evaporating formalin was progressively replaced by distilled water without letting the water level rise above the top of the cores (so one could be sure that cores appearing wet on the surface were indeed saturated). Once saturated, the cores were ready for macroporosity measurement. Most cores became saturated after 24 hours but some cores were hydrophobic and did not become saturated for up to 22 days in extreme cases.

Macroporosity was measured via the assessment of the moisture release characteristic. Moisture release from the core samples was achieved using the pressure plate extractor approach similar to that described by Reeve and Carter (1991). The saturated cores were placed on porous, ceramic plates in a pressure extractor (Soil Moisture Equipment Corporation) and a constant pressure of 10 kPa (equivalent to -10 kPa matric potential) was applied to them for a period of about 36 hours to remove water from all macropores (i.e. pores larger than 30 μm). It was found that 36 hours was sufficient for the moisture content of the cores to reach equilibrium (outflow from the pressure extractors had ceased). A matric potential of -10 kPa was applied to bring the moisture content of soil cores close to field capacity moisture content (where water has drained from pores that are usually air-filled). Hence, macroporosity is equivalent to the air-filled porosity of a soil and consequently is of significance to plant growth (McLaren and Cameron, 1996). The cores were then weighed on removal from the pressure extractors and again after being oven dried at 105° C overnight (Figure 5.4). The moist (-10 kPa) and oven-dry core weights were used, together with the particle density data to calculate macroporosity.

Figure 5.4. Oven-dried macroporosity core samples from the pre-harvested plot.

The particle density of bulked samples (made-up from 12 individual samples), each representing a soil drainage class, was measured using a STEC Volumeter (high precision automatic He pycnometer, Type VH-100). The use of He pycnometry for the measurement of soil particle density has been described by Bielders *et al.* (1990).

5.2.2.4 Total C

Total C was measured using a high-frequency induction furnace (Shimadzu solid sample module attached to the infrared detector of the Shimadzu 5000a TOC instrument). The total C content of the soil samples was determined by measuring the CO_2 produced using an infrared detector during the combustion (total combustion at 900° C) of 0.2 g of finely ground soil in an O_2 atmosphere. Given the nature of the soil parent materials and weathering regime (Chapter 3, section 3.3.3), it is very unlikely that any of the soils within the study area contain significant amounts of inorganic C. Therefore, total C probably closely approximates organic C.

5.2.3 Terrain analysis: calculation of quantitative terrain attributes

The terrain analysis involved the development of a digital elevation model (DEM) and the derivation of a suite of terrain attributes from it. The geographic information system (GIS) ARCGIS 8.2, including ARCINFO 8.2 (ESRI, 2002), was used to perform the terrain analysis. Eight terrain attributes were derived: (1) slope steepness, (2) aspect, (3) plan curvature, (4) profile curvature, (5) total curvature, (6) elevation, (7) relative elevation, and (8) topographic wetness index. The first five attributes listed describe the morphology of the land surface whereas elevation and relative elevation are related to landscape position. Topographic wetness index is a terrain-based measure of potential soil wetness.

Prior to commencing the terrain analysis, it was necessary to perform two tasks. Firstly, the co-ordinates of the sample points (together with their associated soil data) were imported into ARCMAP from text files using the *add x, y data* tool. The co-ordinates were converted to shape-files using the *data export* tool and from shape-files to point coverages using ARCTOOLBOX. A shape-file containing a rectangular polygon to represent a plot boundary was also created for each plot. Secondly, an area encompassing both the pre- and post-harvested plots and their drainage systems (i.e. the predictive modelling experimental area, PMEA) was clipped from the source data coverages of the whole study area for the purpose of performing the terrain analysis. A larger area than that of the plots was used for the terrain analysis because the calculation of some of the terrain attributes within the plots may be reliant on data existing outside of the plot boundaries (e.g. topographic wetness index). Consequently, the terrain attribute grids covered the entire PMEA rather than each plot alone.

The 5-m contour and spot height data contained within the PMEA were used for developing the DEM and subsequently deriving the terrain attributes. Stream and road coverages were also included for presentation purposes. The contour data and other topographic coverages were provided by Carter Holt Harvey Forests Ltd.

5.2.3.1 Elevation: the digital elevation model

A 5-m resolution DEM was created from the contour and point coverages using the *topogrid* command in the *arc* module of ARCINFO, which is based on the ANUDEM software programme developed by Hutchinson (1989). The boundary of the DEM (corresponding to the boundary of the PMEA) was set by the polygon coverage that was used initially to clip out the input data. The DEM was created with the drainage enforcement routine enabled to remove all spurious depressions (sinks) to ensure that a hydrologically correct DEM was created.

The stream coverage was not used in creating the DEM because it was found that the inclusion of streams generated a DEM with very deeply entrenched streams and rivers which, from field experience, was clearly inaccurate. Three diagnostic output files were also generated in creating the DEM to allow for an assessment of its quality: (1) a point coverage showing remaining sinks, (2) a line coverage of the stream and ridge lines, and (3) a text file noting all details of the DEM creation. Sinks, to a depth of 50 m, which were not removed by the enforcement algorithm in *topogrid*, were removed using the *fill* command in the *grid* module of ARCINFO. The resulting sink-filled DEM was used for the derivation of the other terrain attributes. In addition to being the basis for the derivation of all other terrain attributes, the DEM also represents the elevation terrain attribute.

5.2.3.2 Surface morphology

The five terrain attributes that describe the morphology of the land surface (slope steepness, aspect, plan curvature, profile curvature, and total curvature) were calculated from the 5-m DEM using the *curvature* command in the *grid* module of ARCINFO, which applies the partial quadratic polynomial equation of Zevenbergen and Thorne (1987):

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I$$

where Z is elevation and the parameters A . . . I were calculated from the surface within a moving 3x3-cell window. The parameters were calculated according to the following equations:

$$A = [(Z_1 + Z_3 + Z_7 + Z_9)/4 - (Z_2 + Z_4 + Z_6 + Z_8)/2 + Z_5]/L^4$$

$$B = [(Z_1 + Z_3 - Z_7 + Z_9)/4 - (Z_2 - Z_8)/2]L^3$$

$$C = [(-Z_1 + Z_3 - Z_7 + Z_9)/4 - (Z_4 - Z_6)/2]/L^3$$

$$D = [(Z_4 + Z_6)/2 - Z_5]/L^2$$

$$E = [(Z_2 + Z_8)/2 - Z_5]/L^2$$

$$F = (-Z_1 + Z_3 + Z_7 - Z_9)/4L^2$$

$$G = (-Z_4 + Z_6)/2L$$

$$H = (Z_2 + Z_8)/2L$$

$$I = Z_5$$

where Z_1 to Z_9 are the elevation values and L is the cell width of the nine cells that comprise the 3x3-cell window (Figure 5.5) (Zevenbergen and Thorne, 1987; ESRI, 2002).

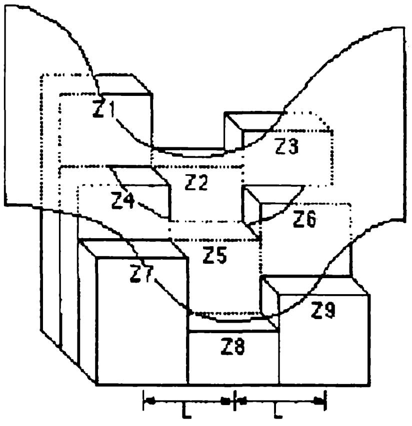

Figure 5.5. Diagram illustrating the components of the polynomial equation of Zevenbergen and Throne (1987) (From ARCGIS help notes, ESRI, 2002).

Slope steepness and aspect (calculated in units of degrees) are the first-order derivates of the DEM surface whereas the three curvature attributes (in units of 1/100 m) are the second-order derivatives.

Slope steepness

Slope steepness is the rate of maximum change in elevation and is defined by a plane tangent to the DEM surface. Slope angle (β) was calculated as:

$$\beta = \arctan\left(G^2 + H^2\right)^{0.5}$$

The resulting grid of slope steepness was an optional output of the *curvature* command (Zevenbergen and Thorne, 1987; ESRI, 2002).

Aspect

Aspect is the direction a slope faces and in this study was represented as compass directions (between 1 and 360°, clockwise from north). Aspect (Ψ) was calculated from the 5-m DEM using the *curvature* command in the *grid* module of ARCINFO according to the equation:

$$\Psi = \arctan\left(\frac{-H}{-G}\right)$$

The aspect output grid was an optional output of the *curvature* command (Zevenbergen and Thorne, 1987; ESRI, 2002).

Plan curvature

Plan curvature is the curvature of a surface perpendicular to the direction of slope. It influences the divergence and convergence of water flow. Positive plan curvatures (convex slopes) indicate water divergence whereas negative plan curvatures (concave slopes) indicate water convergence (e.g. see Figure 4.3 in Chapter 4, section 4.2.4.3). Plan curvature (K_{pl}) was calculated using:

$$K_{pl} = 2\frac{(DH^2 + EG^2 - FGH)}{(G^2 + H^2)}$$

The plan curvature grid was an optional output of the *curvature* command (Zevenbergen and Thorne, 1987; ESRI, 2002).

Profile curvature

Profile curvature is the curvature of a surface in the direction of slope. It influences the velocity of water flow and, consequently, rates of erosion and deposition. In contrast to plan curvature, positive profile curvatures indicate water convergence (decelerated flow; concave slopes) whereas negative profile curvatures indicate water divergence (accelerated flow; convex slopes) Profile curvature (K_{pr}) was calculated using:

$$K_{pr} = -2\frac{(DG^2 + EH^2 + FGH)}{(G^2 + H^2)}$$

The profile curvature grid was an optional output of the *curvature* command (Zevenbergen and Thorne, 1987; ESRI, 2002).

Total curvature

Total curvature, also known simply as curvature, provides a general description of the curvature of the land surface. The curvature of a slope in both plan and profile is taken into account. For example, a slope with a strongly convex plan and profile shape would have a large, positive total curvature value, whereas slopes with a strongly convex plan shape and a concave profile shape would have a more neutral (closer to zero) total curvature value. Therefore, it can be a useful descriptor of the overall convergence and divergence of water flow. Like plan curvature, positive total curvatures indicate water divergence whereas negative curvatures indicate water convergence. Total curvature (K) was calculated using:

$$K = K_{pl} - K_{pr}$$

The total curvature grid was the primary output of the *curvature* command (Zevenbergen and Thorne, 1987; ESRI, 2002).

5.2.3.3 Relative elevation

Relative elevation is a measure of relative landscape position — the elevation of a given point in the landscape relative to the elevation of the surrounding points. Relative landscape position can be a useful indicator of wetness (Gallant and Wilson, 2000) because areas high in the landscape (with few surrounding slopes) tend to be drier whereas areas that are low in the landscape (many surrounding slopes contributing to water flow) tend to be wetter. Relative elevation was defined to be the elevation at a given point (a DEM cell) expressed as a relative proportion (percentage) of the elevation range of surrounding cells within a 13-cell radius. Relative elevation (Z_r) was calculated as an arithmetic function in the *grid* module of ARCINFO using the following equation:

$$Z_r = \frac{Z_\chi - Z_{min}}{Z_{max} - Z_{min}} \times 100$$

where Z_χ is the elevation at a given cell (taken from the DEM), Z_{min} is the minimum elevation within the surrounding neighbourhood of cells, and Z_{max} is the maximum elevation within the surrounding neighbourhood of cells (adapted from Gallant and Wilson, 2000). The Z_{min} and Z_{max} values applied to each cell were calculated within a circular local neighbourhood with a radius of 13 cells using the *focalmin* and *focalmax* commands in the *grid* module of ARCINFO, respectively. Gallant and Wilson (2000) stated that the size of the local neighbourhood used for determining Z_r should approximate slope length in order to give Z_r more physical relevance. The average slope length in the study area was estimated to be approximately 26 cells (130 m) and so a neighbourhood radius of 13 cells (65 m) was derived. The approach to calculating relative elevation used in this study represents an improvement over the approach suggested for use with ARCINFO by Gallant and Wilson (2000) which used Z_{max} and Z_{min} values for the entire area in question rather than for a moving local neighbourhood.

5.2.3.4 Topographic wetness index

Topographic wetness index (variously known as the wetness index or the compound topographic index) is a secondary terrain attribute that describes potential soil wetness at a given point in the landscape (Moore *et al.*, 1993). Potential wetness is taken to be a function of two primary terrain attributes: (1) specific catchment area, and (2) slope steepness (described in further detail below). Topographic wetness index (*W*) was calculated using the equation:

$$W = \ln\left(\frac{A_s}{\tan\beta}\right)$$

where A_s is the specific catchment area and β is slope steepness (in radians). The form of the topographic wetness index used in this study assumes steady-state conditions and uniform soil hydraulic conductivity (Wilson and Gallant, 2000a, 2000b).

The calculation of topographic wetness index was automated using an Arc Macro Language (AML) script modified from that written by Evans (2001). The AML ensures that all sinks in the DEM are filled before beginning the calculations and replaces all zero slope values with the nominal value of 0.001 to avoid the division of A_s by zero.

Specific catchment area

Specific catchment area is the area of slope above a given point that is contributing to water flow to that point per unit length of contour (Gallant and Wilson, 2000). A_s was calculated as a *grid* arithmetic function in the *grid* module of ARCINFO using the equation:

$$A_s = \left(\frac{A}{l}\right)$$

where A = (flow accumulation + 1) × (cell area)

and where A is the upslope contributing area, l is the unit contour length (taken to be cell width), flow accumulation is the number of cells that contribute to water flow into a given cell, and cell area is in units of m^2. The *flow accumulation* command in the *grid* module of ARCINFO was used to calculate flow accumulation. Before it could be calculated, the direction of flow had to be determined. The *flow direction* command was used to calculate the direction of flow from each cell by determining the steepest down-slope path. ARCINFO uses the deterministic eight-node (D8) algorithm of O'Callaghan and Mark (1984) to calculate flow direction. With this algorithm, water is described as flowing in one of eight possible directions (the eight neighbouring cells) (Gallant and Wilson, 2000; ESRI, 2002).

Slope steepness

The slope component of the topographic wetness index equation was initially calculated in degrees using the *curvature* command in the *grid* module of ARCINFO. Slope (degrees) was then converted to units of radians:

$$\beta(\text{radians}) = \frac{\beta(\text{degrees}) \times \left(\frac{\pi}{2}\right)}{90}$$

5.2.3.5 Extraction of terrain attributes

The value of each terrain attribute at each sample point in both plots was extracted using the *latticespot* command in the ARC module of ARCINFO. The *latticespot* command calculates the value of an attribute (represented by a lattice or grid surface) at locations corresponding to each point in a point coverage (e.g. pre- and post-harvested sample point coverages) by bilinear interpolation, and places the extracted data in the Polygon Attribute Table (PAT) of the point coverage (ESRI, 2002). The extracted terrain attribute data were exported from the PAT files of the sample point coverages as *dbase* files and imported into MICROSOFT EXCEL for further analysis.

5.2.4 Statistical analysis

All statistical analyses were performed using SAS/STAT version 8 (SAS Institute, 2000).

5.2.4.1 Preliminary data analysis

An examination of the target property and terrain attribute data indicated that transformation of some of the target properties or attributes was required to obtain normal distributions. Data requiring transformation were transformed by calculating the square root, natural log, or inverse value of the target property or attribute concerned, depending on the strength of transformation required. Available K and macroporosity data were transformed by taking the square root whereas available Mg and available P values were transformed by taking the natural log of the data. Topsoil pH and total C data required no transformations. Wetness index, the only terrain attribute that required transformation, was transformed by taking the inverse of the data.

Aspect, a circular attribute, was converted into two separate attributes to allow for its use in the multi-linear regression modelling: (1) sin-aspect, and (2) cos-aspect, by calculating the sine and cosine of aspect, respectively (Bourennane *et al.*, 2000). Although split into two separate attributes, both were linked during the stepwise regression analysis meaning that if one of the aspect attributes was selected, the other was necessarily selected also.

Correlation matrices of the terrain attributes were examined to ensure that two or more highly correlated terrain attributes were not used together for the prediction of a given target property (i.e. not included in the same multi-linear regression equation). Highly correlated terrain attributes were defined to be those with a Pearson correlation coefficient above 0.6 or below -0.6 (M. Kimberley, 11 August, 2003, personal communication).

5.2.4.2 Magnitude and variance of the target properties

The impact of forest harvesting on the magnitude and variance of the target properties was assessed by directly comparing the mean (magnitude) and variance of each target property in the pre-harvested plot with that in the post-harvested plot. Mean and variance values were calculated using the data points of the development set within each plot. Furthermore, the means and variances were adjusted for modified soil drainage class because the target properties are strongly related to these drainage classes (section 5.3.2.1) which do not occur with the same abundance in both plots (Chapter 4, section 4.3.1.4). Target property means were compared using a least-squares-means-analysis of variance (using SAS/STAT) whereas the variances were compared using an F probability distribution test. In both tests, a *P* value less than 0.05 (corresponding to the 5% level of significance) was taken to indicate a significant difference in the means or variances.

5.2.4.3 Relating the target properties to drainage classes, landscape units, and soil-landscape units

The relationships of the target properties to the soil drainage classes (modified and broad), landscape units, and soil-landscape units were established by grouping the target property data (development set only) of each plot by the aforementioned classes and units and calculating and comparing the target property means of each class or unit within each plot. The impacts of forest harvesting on these relationships were assessed by comparing and contrasting the relationships found in the pre-harvested plot with those in the post-harvested plot. The target property means of the classes and units in the pre-harvested plot were also directly compared with those of the corresponding classes and units in the post-harvested plot (e.g. mean topsoil pH of the Well Drained soils in the pre-harvested plot was compared to mean topsoil pH of the Well Drained soils in the post-harvested plot). The target property means were compared using a least-squares-means analysis of variance (using SAS/STAT) and a P value less than 0.05 was taken to indicate a significant difference in the means.

5.2.4.4 Relating the target properties to the terrain attributes

The relationships between the terrain attributes (section 5.2.3) and the target properties were assessed using the squared multiple correlation statistic (R^2) values which were calculated during the development of the stepwise, least-squares, multi-linear regression (MLR) models for the spatial prediction of the target properties (Chapter 6, section 6.2.1.1). The MLR technique involved the calculation of regression models describing the relationships between the target properties and the terrain attributes. Only those terrain attributes that were significantly ($P < 0.01$) correlated to the target property in question were retained for use in the regression model. The squared multiple correlation statistic describes the proportion of variation in a dependent variable (e.g. a target property) explained by the explanatory variables (e.g. the terrain attributes) in a multi-linear regression model. Thus, R^2 is commonly expressed as a percentage (by multiplying by 100). Terrain attributes that are strongly linearly correlated to a target property will explain a large proportion of the variation in that property whereas terrain attributes that are weakly correlated will explain only a small proportion of the variation. Partial R^2 values, describing the proportion of the variation in a target property explained by an individual terrain attribute (among other terrain attributes) used in a multi-linear regression model, were calculated in addition to the R^2 value for the model itself.

5.3 Results and discussion

The results pertaining to the three aspects of this study are presented, described, and discussed each in turn. Firstly, the impacts of forest harvesting on the magnitude and variance of the target properties are examined. Secondly, the impacts of harvesting on the relationships between the target properties and the soil drainage classes are considered. Finally, the impacts of harvesting on the relationships between the target properties and the landscape units, soil-landscape units, and terrain attributes are described. The results are relevant to the interpretation of the performance of most of the target property prediction techniques that are compared in Chapter 6.

5.3.1 Impacts of harvesting on the magnitude and variance of the target properties

The means and variances of the target properties in both plots are presented (Table 5.1) in order to evaluate the impacts of forest harvesting on these values.

Table 5.1. Mean and variance values of the target properties in both plots. Mean and variance values followed by the same letter are not significantly different ($P < 0.05$).

Property†	**Plot‡**	**Mean***	**Variance***
Topsoil pH	Pre	4.98 a	0.09 a
	Post	4.83 b	0.07 b
Mg (cmol$_c$/kg)^1	Pre	2.99 a	0.19 a
	Post	2.60 b	0.13 b
P (ppm)^1	Pre	13.43 a	0.24 a
	Post	18.87 b	0.29 a
K (cmol$_c$/kg)	Pre	0.46 a	0.03 a
	Post	0.56 b	0.02a
MP (%)	Pre	11.92 a	1.39 a
	Post	9.69 b	1.41 a
TC (%)	Pre	3.62 a	1.50 a
	Post	4.90 b	2.26 b

* Means and variances of soil drainage classes were adjusted (pooled) to remove the effect of drainage class. † MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. ^{1} Geometric means presented.

The data in Table 5.1 show that forest harvesting had a significant ($P < 0.05$) affect on the means of all the target properties. The means of some target properties (topsoil pH, available Mg, and macroporosity) were significantly reduced by harvesting whereas the means of the other target properties were significantly increased by harvesting (available P, available K, and total C). The data also show that forest harvesting had a significant ($P < 0.05$) affect on the variance of some target properties (topsoil pH, available Mg, and total C) (Table 5.1). Harvesting significantly reduced the variances of topsoil pH and available Mg whereas the variance of total C was significantly increased by harvesting. The variances of the other the target properties (available P, available K, and macroporosity) were unaffected.

The significant ($P < 0.001$) increase in mean total C (Table 5.1) after harvesting is probably due to the large amount of organic material, mostly in the form of 'slash', that was deposited across the post-harvested plot (Figure 5.6) at the time of harvesting (approximately two years prior to sampling). The term 'slash' refers to the logs, branches, and foliage that are discarded during the harvesting process and left to decompose on the soil surface. Ganjegunte *et al.* (2004) reported a net release of carbon from *Pinus radiata* thinning slash within the first two years of decomposition. Some of the forest litter cover that existed prior to harvesting may also have been incorporated into the surface soil by harvesting disturbance and thus contributed to the increase in mean total C. Furthermore, the removal of the forest canopy left the deposited slash and litter cover in an exposed environment where decomposition probably proceeded more rapidly than it would have under a closed canopy of mature pine trees (i.e. the pre-harvested plot). The mean total C in the pre-harvested plot (3.6%) is classed as low according to the ratings for soil chemical properties given by Blakemore *et al.* (1987) whereas in the post-harvested plot, a medium concentration was found (4.9%) which underscores the significance of the increase in mean total C after harvesting.

Figure 5.6. Slash deposition across the post-harvested plot. Note the extensive cover of weeds and grasses and the discontinuous nature of the slash deposits.

The significant ($P < 0.01$) increase in the variance of total C after harvesting can probably be attributed to the deposition of the slash in relatively discrete piles (Figure 5.6). Litter material may also have been washed down-slope from the upper landscape positions and accumulated in lower positions, thus contributing to the uneven distribution of organic material across the land surface.

The significant ($P < 0.001$) decrease in mean topsoil pH (Table 5.1) observed after harvesting has been reported in other studies (e.g. Schmidt *et al.*, 1996) and can probably be attributed to an increase in organic acids produced during the decomposition of slash and litter (Schmidt *et al.*, 1996). Increased microbial activity may occur in response to harvesting-related organic matter (total C) addition and soil disturbance. Although mean topsoil pH in the post-harvested plot was significantly lower than that in the pre-harvested plot, the means in both plots are classed as low (strongly acid) according to the ratings of Blakemore *et al.* (1987). The cause of the significant ($P < 0.05$) reduction in the variance of topsoil pH after harvesting is uncertain.

The significant ($P < 0.001$) post-harvesting increase in the mean concentrations of available P and K in the soil (Table 5.1) is probably also associated with the increase in soil organic matter that resulted from the forest harvesting process. The greater availability of organic matter in the surface soil may have allowed for an increase in soil microbial activity which, in turn, resulted in the enhanced cycling and availability of nutrients such as P and K (Johnson and Todd, 1998). An available P (Bray P) value of 12 ppm is sometimes used by the New Zealand forestry industry as a threshold for making P fertiliser management decisions (Payn and Thwaites, 1998; Palmer *et al.*, 2004). Available P values > 12 ppm are considered sufficient for tree growth whereas values < 12 ppm are considered insufficient and could thus prompt the application of P fertiliser (Ballard, 1974). The concentration of mean available P was only slightly above the threshold in the pre-harvested plot (13.4 ppm) whereas in the post-harvested plot, the concentration of mean available P (18.9 ppm) was well in excess of the threshold which indicates that P fertiliser is not required in that part of southern Mahurangi Forest subsequent to harvesting. According to the ratings of Blakemore *et al.* (1987), the levels of mean available K are low in the pre-harvested plot and medium in post-harvested plot which suggests that forest harvesting has resulted in the elevation of mean available K from potentially deficient to adequate levels.

The cause of the significant ($P < 0.01$) reduction in mean available Mg after harvesting (Table 5.1) is uncertain. However, the concentration of mean available Mg in both plots is considerably higher than the management threshold proposed by Payn *et al.* (1996) for available (Bray) Mg, where values < 0.75 cmol_c/kg indicate deficiency. Moreover, the levels in both plots are classed as medium according to the ratings of Blakemore *et al.* (1987). Thus, Mg fertiliser is probably not required after harvesting even though the levels of available Mg were significantly reduced. The significant ($P < 0.05$) decrease in the variance of available Mg after harvesting may, like topsoil pH, be associated with the change in vegetation cover which, in turn, may have caused the nutrient cycling in the topsoil to become slightly more uniform across the landscape.

The mean macroporosity of the soil was significantly ($P < 0.05$) lower in the post-harvested plot than in the pre-harvested plot (Table 5.1), suggesting that soil compaction occurred in the post-harvested plot as a consequence of harvesting. Soil compaction has often been associated with forest harvesting activities (McMahon *et al.*, 1999; McNabb *et al.*, 2001; Block *et al.*, 2002). The macroporosity of the soil was probably reduced by a combination of the hauling (dragging) of felled logs across the ground and the use of heavy harvesting vehicles (skidders of bulldozers) on the upper parts of the landscape (Figure 5.7). A management threshold of 10% is sometimes applied to macroporosity data (Startsev and McNabb, 2001). Macroporosity values above the 10% threshold generally indicate that air and water movement is sufficient for root growth whereas values below 10% can indicate impeded air and water movement which may lead to restricted root growth (Greacen and Sands, 1980). Mean macroporosity was above the 10% management threshold in the pre-harvested plot (11.9%) but was just below the management threshold in the post-harvested plot (9.7%), indicating that forest harvesting has diminished the ability of the surface soil to transmit air and water to the extent that seedling growth could be adversely affected. Some remedial work such as mounding or ripping may be required to increase the macroporosity of the soil after harvesting.

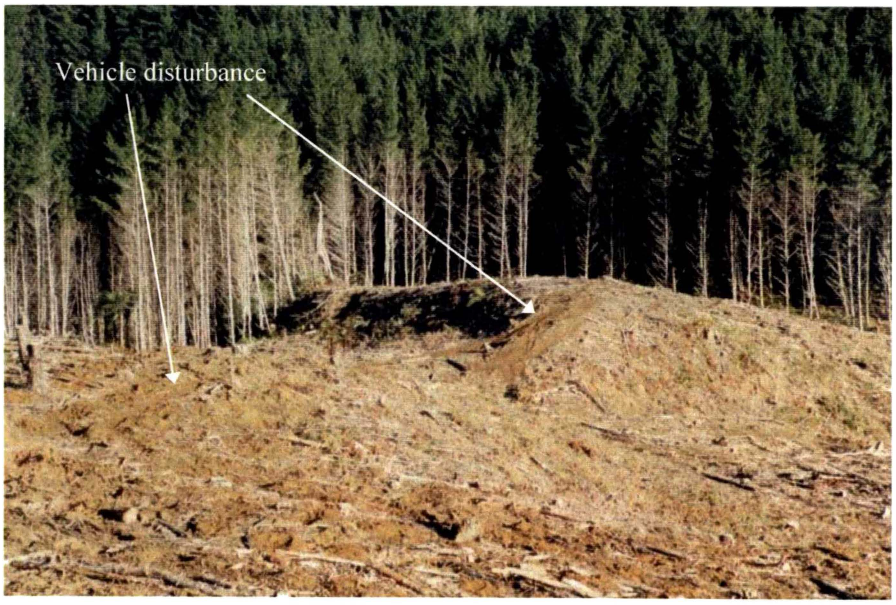

Figure 5.7. Example of the effects of vehicle trafficking during harvesting on the surface soil of a low ridge summit in southern Mahurangi Forest.

5.3.2 Impacts of harvesting on the relationships between the target properties and the drainage classes

5.3.2.1 Modified soil drainage classes

The relationships between the target properties and the modified soil drainage classes are examined by considering the differences in the target property means of these classes in both plots (Table 5.2).

Table 5.2. Mean target property values of the modified soil drainage classes in both plots. Means followed by the same letter are not significantly different ($P < 0.05$).

		Modified soil drainage classes§			
Property†	**Plot‡**	**WD**	**ID**	**SPD**	**PD**
Topsoil pH	Pre	4.75 ab	4.86 b	5.10 c	5.23 c
	Post	4.67 a	4.73 a	4.86 b	5.06 c
Mg (cmol$_c$/kg)^1	Pre	2.15 a	2.20 a	4.07 b	4.14 b
	Post	2.32 a	2.41 a	2.53 ac	3.26 bc
P (ppm)^1	Pre	9.13 a	10.17 a	14.37 b	24.35 d
	Post	14.08 b	14.37 b	17.50 b	35.79 c
K (cmol$_c$/kg)	Pre	0.36 a	0.40 ac	0.54 b	0.52 bc
	Post	0.51 b	0.54 b	0.54 b	0.66 b
MP (%)	Pre	18.08 a	14.00 b	7.71 c	7.89 c
	Post	13.33 b	9.38 c	6.88 c	9.17 bc
TC (%)	Pre	3.83 ac	3.66 ad	3.10 d	3.92 ae
	Post	5.00 b	4.97 b	4.43 bce	5.20 b

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § WD = well drained soils, ID = imperfectly drained soils, SPD = somewhat poorly drained soils, PD = poorly drained soils (defined in Chapter 4, section 4.3.1.2). ^{1} Geometric means presented.

Relationships in the pre-harvested plot

Most target properties were generally strongly related to the modified soil drainage classes in the pre-harvested plot (Table 5.2). For all target properties, except total C, the data appear to be separated into two fairly distinct groups of drainage classes. The first group includes the Well and Imperfectly Drained soils (i.e. the Dry soils) and the second group includes the Somewhat Poorly and Poorly Drained soils (i.e. the Wet soils). These groups correspond to the Dry and Wet broad drainage classes that were defined in Chapter 4 (section 4.3.1.3) and are examined more closely in section 5.3.2.2. The Well and Imperfectly Drained soils generally had similar means and both tended to be significantly ($P < 0.05$) different from the means of the Somewhat Poorly and Poorly Drained soils which were often similar. The separation between these two groups was clear and straight-forward for some target properties (topsoil pH and available Mg), but for other target properties (available P, available K, and macroporosity) the relationships were a little more complex. Nevertheless, the distinction between the two groups held true for most target properties even if only from a practical, management-related, view point.

In the straight-forward case of topsoil pH and available Mg (Table 5.2), the Well and Imperfectly Drained soils had similar means and both were significantly ($P < 0.001$) lower than the means of the Somewhat Poorly and Poorly Drained soils which were similar. Despite these statistical differences, it is unlikely that the two groups of drainage classes would require different management in terms of topsoil pH and available Mg because all classes were strongly acid and had adequate levels of available Mg (Blakemore *et al*, 1987).

With respect to available P, the Well and Imperfectly Drained soils had similar means and both were significantly ($P < 0.01$) lower than those of the Somewhat Poorly and Poorly Drained soils (Table 5.2). However, the mean of the Somewhat Poorly Drained class was also significantly ($P < 0.001$) lower than that of the Poorly Drained class. Despite the Somewhat Poorly and Poorly Drained soils being significantly different, the available P values of both classes were above the 12 ppm management threshold. Therefore, the Somewhat Poorly and Poorly Drained soils could be considered similar, with respect to available P, from a management perspective. Furthermore, the mean available P values of the Well and Imperfectly Drained soils were below the 12 ppm threshold which suggests that these soils should be managed differently from the Somewhat Poorly and Poorly Drained soils in terms of available P.

In the case of macroporosity, the Well and Imperfectly Drained soils had significantly ($P < 0.05$) different means and both were significantly ($P < 0.01$) greater than the means of the Somewhat Poorly and Poorly Drained soils which were similar (Table 5.2). Although the mean macroporosity of the Well Drained soils was significantly greater than that of the Imperfectly Drained soils, the means of both classes were above the 10% management threshold. Thus, the Well and Imperfectly Drained soils could be considered similar, with respect to macroporosity, from a management perspective. Moreover, the mean macroporosity values of the Somewhat Poorly and Poorly Drained soils were below the 10% threshold which indicates that these soils could be managed differently to the Well and Imperfectly Drained soils in terms of macroporosity.

The Well and Imperfectly Drained soils had similar mean available K values as did the Somewhat Poorly and Poorly Drained soils (Table 5.2). However, the mean of the Well Drained class was significantly ($P < 0.01$) lower than those of the Somewhat Poorly and Poorly Drained soils. Furthermore, the mean available K of the Imperfectly Drained class was significantly ($P < 0.05$) lower than that of the Somewhat Poorly Drained class yet similar to that of the Poorly Drained soils. Nevertheless, the means of the Well and Imperfectly Drained soils are classed as low whereas those of the Somewhat Poorly and Poorly Drained soils are classed as medium according to the ratings of Blakemore *et al.* (1987). Therefore, the two drainage class groups could potentially be management differently.

Total C was the target property least strongly-related to the modified drainage classes with the Well, Imperfectly, and Poorly Drained classes having similar means (Table 5.2). The Imperfectly and Somewhat Poorly Drained soils also had similar means whereas the means of the Well and Poorly Drained soils were significantly ($P < 0.05$) greater than that of the Somewhat Poorly Drained soils.

The data in Table 5.2 also show that drainage-related trends exist for all target properties. The means of topsoil pH, available Mg, and available P increased as the soil drainage became progressively more impeded (i.e. as the soil got wetter). A similar trend was also observed for available K. However, mean available K increased as the drainage became poorer only as far as the Somewhat Poorly Drained class and then decreased very slightly in the Poorly Drained class. In contrast, means of macroporosity and total C decreased as the drainage became more impeded as far as the Somewhat Poorly Drained class and then increased in the Poorly Drained class (macroporosity increased only slightly whereas total C increased by a relatively large amount).

Relationships in the post-harvested plot: the impacts of harvesting

The relationships between the target properties and the modified drainage classes are generally weaker in the post-harvested plot than in the pre-harvested plot (Table 5.2). It is evident that forest harvesting has altered and obscured these relationships. For some target properties (available Mg, available P, and macroporosity), three of the four modified drainage classes were found to have similar mean values whereas for other target properties (available K and total C), no differences were observed between the classes. The modified drainage classes were most strongly differentiated with respect to topsoil pH after harvesting.

The means of the Well, Imperfectly, and Somewhat Poorly Drained soils were similar with respect to available Mg and available P (Table 5.2). The mean available Mg of the Poorly Drained soils was significantly ($P < 0.05$) greater than those of the Well and Imperfectly Drained soils but was similar to the mean of the Somewhat Poorly Drained soils. In contrast, the mean available P of the Poorly Drained soils was significantly ($P < 0.001$) greater than those of all other drainage classes. The data in Table 5.2 show that the mean available Mg of the Somewhat Poorly Drained class was significantly ($P < 0.001$) decreased after harvesting. This reduction, which brought the mean of Somewhat Poorly Drained soils more into-line with those of the Well and Imperfectly Drained soils, is largely responsible for the greater similarity in the modified drainage classes (i.e. weaker relationships) with respect to available Mg. The weaker relationship between available P and the modified drainage classes is due mainly to the significant ($P < 0.01$) post-harvesting increase in the means of the Well and Imperfectly Drained soils. Hence, the means of these soils are similar to that of the Somewhat Poorly Drained soils with respect to available P.

In contrast to available Mg and P, the means of the Imperfectly, Somewhat Poorly, and Poorly Drained soils were similar with respect to macroporosity (Table 5.2). The mean of the Well Drained class was significantly ($P < 0.05$) greater than those of the Imperfectly and Somewhat Poorly Drained soils but similar to that of the Poorly Drained class. The weakening of the relationships between macroporosity and the modified drainage classes after harvesting is due to the significant ($P < 0.05$) post-harvesting reduction in the means of the Well and Imperfectly Drained soils, which resulted in these soils having means more similar to those of the Somewhat Poorly and Poorly Drained soils. The significantly lower mean macroporosity values of the Well and Imperfectly Drained soils after harvesting probably reflect harvesting-related soil compaction on the more elevated, upper parts of the landscape where the Well and Imperfectly Drained soils are most common.

For available K and total C, all modified drainage classes had similar means (Table 5.2). The modified drainage classes were relatively well differentiated with respect to mean available K in the pre-harvested plot. Therefore, forest harvesting has substantially weakened the relationships between available K and the modified drainage classes. The reduction in class differentiation is due to the significant ($P < 0.01$) post-harvesting increase in the mean available K values of the Well and Imperfectly Drained soils, which resulted in these soils having means similar to those of the Somewhat Poorly and Poorly Drained soils. The impact of harvesting on total C was not a severe as it was for available K because the relationship between total C and the modified drainage classes was weak prior to harvesting (i.e. in the pre-harvested plot). The mean total C values of all modified drainage classes were significantly ($P < 0.01$) increased after harvesting. Consequently, the relative differences between the classes were only slightly reduced.

With respect to topsoil pH, the modified drainage classes remained relatively strongly differentiated after harvesting (Table 5.2). The Well and Imperfectly Drained soils had similar means and both were significantly ($P < 0.05$) lower than those of the Somewhat Poorly and Poorly Drained soils. Furthermore, the mean of the Somewhat Poorly Drained soils was significantly ($P < 0.05$) lower than that of the Poorly Drained soils. The significant ($P < 0.001$) post-harvesting reduction in the mean topsoil pH of the Somewhat Poorly Drained class was sufficient to result in the mean of this class becoming significantly different from that of the Poorly Drained class in the post-harvested plot. The significant difference in the mean topsoil pH values of the Imperfectly Drained and Somewhat Poorly Drained soils observed in the pre-harvested plot was maintained after harvesting due to the significant ($P < 0.05$) reduction in the mean of the Imperfectly Drained soils.

From a management perspective, all modified drainage classes could be treated similarly with respect to most target properties (topsoil pH, available Mg, available P, available K, and total C) after forest harvesting (Table 5.2). All classes were strongly acid and had adequate or medium levels of available P, K, Mg, and total C. Thus, little post-harvesting action is required with respect to these properties. Macroporosity was the only target property for which the modified drainage classes could be managed differently after harvesting. The macroporosity of the Well Drained soils was adequate (above the 10% threshold) whereas the macroporosity of the other classes was inadequate (below the 10% threshold). Therefore, some post-harvesting amelioration of compacted soils (e.g. the Imperfectly Drained soils) may be required to avoid the restriction of seedling growth.

The drainage-related trends observed for all target properties after harvesting (i.e. in the post-harvested plot) are essentially the same as those found in the pre-harvested plot (Table 5.2). However, available K had a slightly different trend, generally increasing as the drainage became poorer, and did not decrease in the Poorly Drained class as was the case in the pre-harvested plot. The mean available K values of the Imperfectly and Somewhat Poorly Drained soils were very similar and thus represented a plateau in the trend, however.

5.3.2.2 Broad soil drainage classes

The relationships between the target properties and the broad soil drainage classes are examined by considering the differences in the target property means of these classes in both plots (Table 5.3).

Table 5.3. Mean target property values of the broad soil drainage classes in both plots. Means followed by the same letter are not significantly different ($P < 0.05$).

Property†	Plot‡	Broad soil drainage classes§	
		Dry	Wet
Topsoil pH	Pre	4.79 a	5.15 c
	Post	4.72 a	4.91 b
Mg ($\mathrm{cmol_c/kg}$)[1]	Pre	2.17 a	4.09 c
	Post	2.38 ab	2.71 b
P (ppm)[1]	Pre	9.57 a	17.58 c
	Post	14.30 b	21.25 c
K ($\mathrm{cmol_c/kg}$)	Pre	0.38 a	0.54 b
	Post	0.53 b	0.57 b
MP (%)	Pre	16.30 a	7.78 c
	Post	10.44 b	7.50 c
TC (%)	Pre	3.75 a	3.41 a
	Post	4.98 b	4.64 b

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § Dry = dry soils, Wet = wet soils (defined in Chapter 4, section 4.3.1.3). [1] Geometric means presented.

Relationships in the pre-harvested plot

In the pre-harvested plot, the means of the Dry soils were found to be significantly ($P < 0.001$) different to those of the Wet soils with respect to all target properties except total C (Table 5.3). The Dry soils were significantly more acidic (lower topsoil pH), had significantly lower levels of available nutrients (available Mg, available P, and available K), and had significantly greater macroporosity than the Wet soils. The mean total C values of both broad drainage classes were similar.

In addition to being statistically different in relation to most target properties, the Wet and Dry soils can also be considered different from a management perspective for some target properties (e.g. available P and macroporosity). The mean available P of the Dry soils (9.6 ppm) was below the 12 ppm management threshold whereas the mean of the Wet soils (17.6 ppm) was above it. Hence, the Dry soils are potentially P deficient and a tree-growth response may be obtained by adding P fertiliser to them. In contrast to available P, the mean macroporosity of the Dry soils (16.3%) was above the 10% management threshold whereas the mean of the Wet soils (7.8%) was below the threshold. Tree growth on the Wet soils may be limited due to impeded air and water movement associated with low macroporosity values. Mounding or artificial drainage of the Wet soils may improve tree growth. With reference to the ratings for soil chemical properties of Blakemore *et al.* (1987), the Dry soils are deficient (low) in available K whereas the Wet soils have adequate (medium) levels. Therefore, there is strong potential for the Wet and Dry soils to be managed differently in terms of available P, macroporosity, and possibly available K as well. Although the mean available Mg of the Wet soils was about double that of the Dry soils, both classes had adequate levels of available Mg – medium in the Dry soils and high in the Wet soils. Furthermore, both classes were strongly acid and contained low levels of total C (Blakemore *et al.*, 1987).

Relationships in the post-harvested plot: the impacts of harvesting

The relationships between the target properties and the broad drainage classes were generally weaker after harvesting (Table 5.3). The Wet and Dry soils were only significantly ($P < 0.05$) different for half of the target properties (topsoil pH, available P, and macroporosity). However, the nature of the relationships remained the same as in the pre-harvested plot for these properties: topsoil pH and available P levels were significantly lower and macroporosity was significantly greater in the Dry soils than in the Wet soils. The loss of class differentiation was due to the significant ($P < 0.001$) post-harvesting decrease in the mean available Mg of the Wet soils and to the significant ($P < 0.001$) post-harvesting increase in the mean available K of the Dry soils. In essence, forest harvesting resulted in the Wet soils becoming more like the Dry soils with respect to available Mg, and in the Dry soils becoming more like the Wet soils in relation to available K.

The management-related differences between the broad drainage classes were diminished by forest harvesting to a greater extent than were the statistical differences. Both classes could be managed similarly for all target properties except macroporosity. The mean macroporosity of the Dry soils (10.4%) remained slightly above the 10% management threshold, despite having been significantly ($P < 0.001$) reduced by harvesting, whereas that of the Wet soils (7.5%) remained below the threshold. The mean available P of the Dry soils was significantly ($P < 0.001$) increased after harvesting and consequently exceeded the 12 ppm management threshold whereas that of the Wet soils remained well above the threshold. Both drainage classes have medium concentrations of available Mg and available K (Blakemore *et al.*, 1987). Harvesting significantly ($P < 0.001$) increased in the mean available K of the Dry soils from a low to a medium level whereas the mean available Mg of the Wet soils was significantly ($P < 0.001$) decreased from a high to a medium level after harvesting. The mean total C values of both classes were significantly ($P < 0.001$) increased from low to medium after harvesting whereas mean topsoil pH remained low for both drainage classes.

5.3.3 Justification for modifying the soil drainage classes

The soil drainage classes presently used in New Zealand, and the criteria used to define them (Milne *et al.*, 1995), were modified for the purposes of this study (Chapter 4, section 4.2.4.2). The most substantial modification was the separation of the existing imperfectly drained class into two classes: Imperfectly Drained and Somewhat Poorly Drained (Chapter 4, section 4.3.1.2). The separation was made on the basis of a difference in profile hydromorphology as described in Chapter 4 (i.e. two hydromorphologically distinct profile types were identified). Despite this difference, both the Imperfectly and Somewhat Poorly Drained soils were classified predominantly as Mottled Yellow Ultic (UYM) soils using the New Zealand Soil Classification (NZSC) (Hewitt, 1998). In effect, the Imperfectly Drained class represent the UYM soils of the drier profile type (Whangaripo series) whereas the Somewhat Poorly Drained class represent those of the wetter profile type (Puhoi series).

The pre-harvested plot data presented in Table 5.2 indicate that the hydromorphologically-based separation of the existing imperfectly drained class was appropriate and effective with respect to most of the target properties. The means of the Imperfectly Drained soils were significantly ($P < 0.05$) different from those of the Somewhat Poorly Drained soils for all target properties except total C. The Imperfectly Drained soils were more acidic, had lower levels of available nutrients (Mg, P, and K), and had greater macroporosity than the Somewhat Poorly Drained soils. Moreover, the two drainage classes could be managed differently with respect to some target properties (available P, macroporosity, and available K). The mean available P of the Imperfectly Drained soils was deficient (below the 12 ppm threshold) whereas that of the

Somewhat Poorly Drained soils was sufficient. Also, the level of available K was found to be low in the Imperfectly Drained class and medium in the Somewhat Poorly Drained class (Blakemore *et al.*, 1987). In contrast, the mean macroporosity of the Imperfectly Drained soils was adequate (above the 10% threshold) whereas that of the Somewhat Poorly Drained soils was inadequate. In general, the Imperfectly Drained soils were more similar to the Well Drained soil whereas the Somewhat Poorly Drained soils were more similar to the Poorly Drained soils with respect to most target properties.

At present, all UYM soils are classed as imperfectly drained and are considered to be similar with respect to forest management. The above results (Table 5.2) show that this is definitely not the case in southern Mahurangi Forest. Furthermore, the hydromorphologically-based soil drainage difference observed within the UYM subgroup in this study probably also occurs within the mottled subgroups of most other orders of the NZSC and in other regions (A. E. Hewitt, 27 November, 2002, personal communication). Subject to further research, it is suggested that the New Zealand soil drainage criteria be revised and modified to recognise this important hydromorphological difference. More specifically, the subdivision of the existing imperfectly drained class into two classes is strongly recommended. Although the criteria used in this study represents an improvement over the existing criteria, further research is probably required to comprehensively establish the optimal set of hydromorphological indicators (including critical depth thresholds) to be used to classify soil drainage in New Zealand. However, this study has clearly demonstrated that the abundance and location (within the profile) of redox depletions are extremely important hydromorphological indicators.

The problem of having soils that require different management (i.e. the Imperfectly and Somewhat Poorly Drained soils) encompassed by a single NZSC subgroup could be overcome by incorporating a revised version of the New Zealand soil drainage criteria into the fourth level of the NZSC, the soilform (Clayden and Webb, 1994). The modified drainage classes could replace the permeability classes which are rather impractical for field use because they rely on the estimation of soil hydraulic conductivity from morphological properties (e.g. particle size and degree of packing measurements) which is time consuming and potentially inaccurate. In contrast, soil drainage classes can be accurately and rapidly determined in the field and may provide a more effective assessment of profile permeability and wetness.

Note that only the pre-harvested plot data were referred to in this section because data in the post-harvested plot have been affected by forest harvesting and consequently are not in equilibrium with soil drainage conditions.

5.3.4 Impacts of harvesting on the relationships between the target properties and the landscape

5.3.4.1 Landscape units

The relationships between the target properties and the landscape units are examined by considering the differences in the target property means of these units in both plots (Table 5.4).

Table 5.4. Mean target property values of the landscape units in both plots. Means followed by the same letter are not significantly different ($P < 0.05$).

		Landscape units§			
Property†	**Plot‡**	**Upper**	**Middle-H/D**	**Middle-L/C**	**Lower**
Topsoil pH	Pre	4.70 a	4.84 ce	5.09 d	5.25 f
	Post	4.56 b	4.83 c	4.82 ac	4.96 e
Mg (cmol$_c$/kg)[1]	Pre	1.96 a	2.05 a	4.24 c	4.34 c
	Post	2.04 a	2.65 b	2.56 b	2.84 b
P (ppm)[1]	Pre	9.51 a	9.53 a	13.23 b	24.45 c
	Post	13.09 b	14.91 b	16.34 b	25.11 c
K (cmol$_c$/kg)	Pre	0.32 a	0.37 ab	0.61 c	0.50 de
	Post	0.40 bd	0.59 c	0.58 ce	0.64 c
MP (%)	Pre	14.69 ac	15.84 c	9.98 bd	8.49 bd
	Post	12.48 ab	9.81 bd	6.91 d	7.70 d
TC (%)	Pre	3.93 ae	3.64 ad	3.32 d	3.48 ad
	Post	5.63 b	4.56 c	4.70 c	4.53 ce

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § Middle-H/D = middle-high (pre-harvested) or middle-divergent (post-harvested) units, Middle-L/C = middle-low (pre-harvested) or middle-convergent (post-harvested) units (defined in Chapter 4, section 4.3.2.3). [1] Geometric means presented.

Relationships in the pre-harvested plot

The majority of target properties were reasonably strongly related to the landscape units in the pre-harvested plot (Table 5.4). Furthermore, the data are arranged into two reasonably distinct groups of units for all target properties except topsoil pH and total C. The first group includes the Upper and Middle-H units (i.e. the more elevated, drier parts of the landscape) and the second group includes the Middle-L and Lower units (i.e. the less elevated, wetter parts of the landscape). These groups correspond to the Dry and Wet soil-landscape units that were defined in Chapter 4 (section 4.3.3.2) and are examined further in section 5.3.4.2. The Upper and Middle-H units generally have similar mean values and both tended to be significantly ($P < 0.05$) different from the means of the Middle-L and Lower units which are sometimes similar. The separation between these two groups is clear and straight-forward for some target properties (available Mg and macroporosity), but for other target properties (available P and available K) the relationships were less clear. Nevertheless, the distinction between the two groups holds true for most target properties even if only from a practical, management-related, view point.

In the pre-harvested plot, the pattern of relationships is generally similar to that found between the target properties and the modified drainage classes because the modified drainage classes are themselves fairly strongly related to the landscape units (Chapter 4, section 4.3.3.1). Although the landscape units were not uniform in terms of the modified drainage classes they contained, the Upper and Middle-H units were dominated by Dry soils (Well and Imperfectly Drained) whereas the Middle-L and Lower units were dominated by Wet soils (Somewhat Poorly and Poorly Drained) in the pre-harvested plot.

The relationships are straight-forward in the case of available Mg and macroporosity. The Upper and Middle-H units had similar means and both were significantly ($P < 0.05$) different (lower for available Mg, greater for macroporosity) from the means of the Middle-L and Lower units which were similar. Even though the mean available Mg values of the Upper and Middle-H units were less than half those of the Middle-L and Lower units, different management is probably not required because the levels of available Mg were adequate within all landscape units. However, the Upper and Middle-H units could be managed differently to the Middle-L and Lower units with respect to macroporosity. The mean macroporosity values of the Upper and Middle-H units were adequate (above the 10% management threshold) whereas those of the Middle-L and Lower units were slightly inadequate (below the threshold).

For available P and available K, the relationships were slightly more complex. The Upper and Middle-H units had similar means and both were significantly ($P < 0.05$) lower than the means of the Middle-L and Lower units. However, the mean of the Middle-L unit was also significantly ($P < 0.01$) different (lower for available P, greater for available K) from that of the Lower unit. Despite the statistical difference, both the Middle-L and Lower units had adequate levels of available P (above the 12 ppm management threshold) and medium levels of available K. Therefore, the Middle-L and Lower units could be considered equivalent in terms of available P and K from a management perspective. Furthermore, the levels of available P and K in the Upper and Middle-H units were inadequate (below the threshold for available P and low for available K) and so the Upper and Middle-H units could probably be managed differently from the Middle-L and Lower units with respect to these nutrients.

The greatest differentiation of landscape units occurred for topsoil pH – all units had significantly ($P < 0.05$) different means. However, the means of all units are classed as strongly acid (Blakemore *et al.*, 1987) and so all units could probably be managed similarly with respect to topsoil pH. The relationships were weakest for total C with all landscape units having similar means except for the mean of the Upper unit which was significantly ($P < 0.05$) different from that of the Middle-L unit. Moreover, the mean total C values of all units are classed as low (Blakemore *et al.*, 1987).

Topsoil pH, available Mg, and available P increased down-slope from the drier, more elevated landscape positions to the wetter, less elevated parts of the landscape. A similar trend was observed in available K except that the values reached a maximum in the Middle-L unit before decreasing slightly in the Lower unit. In contrast, macroporosity and total C generally decreased down-slope.

Relationships in the post-harvested plot: the impacts of harvesting

The landscape units are less well differentiated with respect to the target properties in the post-harvested plot than in the pre-harvested (Table 5.4), indicating that the relationships between the target properties and the landscape units are generally weaker in the post-harvested plot than in the pre-harvested. It is evident that forest harvesting has altered the relationships (discussed below), as expected. For most target properties, three of the four landscape units were found to have similar mean values. The landscape units were most strongly differentiated with respect to mean topsoil pH after harvesting.

The distinction between the two groups of landscape units — Upper and Middle-H units on one hand and the Middle-L and Lower units on the other — observed for most target properties in the pre-harvested plot does not occur in the post-harvested plot (Table 5.4). A reduction in landscape unit differentiation was expected because the relationships between the soil drainage classes and the landscape units were slightly different in the post-harvested plot: the Upper, Middle-D, and Middle-C units were dominated by Dry soils whereas only the Lower unit was dominated by Wet soils (Chapter 4, section 4.3.3.1). However, the expected pattern of landscape unit differentiation, corresponding to the soil drainage class-landscape unit relationships, eventuated for only one target property (available P). For all other target properties the observed differences between the landscape units do not reflect the drainage class-landscape unit relationships. Therefore, the patterns of landscape unit differentiation observed for most target properties are most probably the result of forest harvesting impacts. Note that although the two Middle landscape units were defined slightly differently from those in the pre-harvested plot, the Middle-D unit is generally equivalent to Middle-H and the Middle-C unit is generally equivalent to Middle-L in terms of expected soil wetness (Chapter 4, section 4.3.2.2).

The pattern of landscape unit differentiation was simple and straightforward for available Mg, available K, and total C (Table 5.4). The means of the Upper unit were found to be significantly ($P < 0.01$) different (lower for available Mg and K, greater for total C) from those of all other units which were similar. The pattern was similar for macroporosity except that the mean of the Upper unit was similar to that of the Middle-D unit. These observed patterns of unit differentiation contrast sharply with the expected patterns: the means of the Lower unit were expected to be significantly different from those of all other units, which were expected to be similar. In the case of available Mg, the means of the Middle-C and Lower units were significantly ($P < 0.001$) decreased (almost halved) after harvesting whereas the mean of the Middle-D unit was significantly ($P < 0.01$) increased. Thus, the means of these units became similar. The mean of the Upper unit remained relatively low. With respect to available K, the means of the Middle-D and Lower units were significantly ($P < 0.01$) increased after harvesting which resulted in them becoming similar to that of the Middle-C unit which remained unchanged. The mean available K of the Upper unit was also significantly ($P < 0.05$) increased after harvesting but not by enough to remove the difference between this unit and the others. Mean total C values in all landscape units were significantly ($P < 0.01$) increased after harvesting. However, the mean of the Upper unit increased by a greater amount than did those of the other units. Therefore, the mean of the Upper unit became significantly different to all others. In terms of macroporosity, the mean of the Middle-D unit was significantly ($P < 0.01$) decreased after harvesting to become similar to those of the Middle-C and Lower units. However, the decrease was not sufficient to result in the mean values of the Upper and Middle-D units becoming different.

The mean topsoil pH of the Upper landscape unit was significantly ($P < 0.001$) different from that of all other units. The mean of the Lower unit was also significantly ($P < 0.05$) different from that of all other units. The Middle-D and Middle-C units had similar means. The means of the Upper, Middle-C, and Lower units were significantly ($P < 0.05$) decreased after harvesting. The reduction in the mean of the Middle-C unit relative to the unchanged mean of the Middle-D unit resulted in the means of both units becoming similar. In the case of available P, the differences among landscape units were as expected – the mean of the Lower landscape unit was significantly ($P < 0.01$) different from the means of all other units, which were similar. Although this pattern of landscape unit differentiation corresponds to the relationships between the soil drainage classes and landscape units, the results suggest that it may be an artefact of forest harvesting rather than a natural occurrence. The mean available P values of the Upper and Middle-D units were significantly ($P < 0.01$) increased after harvesting to become similar to the mean of the Middle-C unit. If the differences among the units were simply corresponding to natural soil drainage relationships then the mean of the Middle-C unit would have been lower (and thus similar to the means of the Upper and Middle-D units) in the post-harvested plot than in the pre-harvested.

From a management perspective, all landscape units could be treated similarly with respect to most target properties (topsoil pH, available Mg, available P, and total C) after forest harvesting (Table 5.4). All units were strongly acid and had adequate or medium levels of available P, Mg, and total C. Thus, little post-harvesting action is required with respect to these properties. Macroporosity and available K were the only target properties for which the modified drainage classes could be managed differently after harvesting. The macroporosity of the Upper unit was adequate (above the 10% threshold) whereas the macroporosity of the other units was inadequate (below the 10% threshold). Therefore, some post-harvesting amelioration of compacted units (e.g. the Imperfectly Drained soils) may be required to avoid the restriction of seedling growth. In contrast, the level of available K was low in the Upper unit and medium in the other units. Thus the Upper unit could possibly be managed differently from the rest of the landscape with respect to available K.

The landscape trends observed for most target properties in the pre-harvested plot are essentially repeated in the post-harvested plot (Table 5.4). Available P increased down- and across-slope from the drier, more elevated and divergent landscape positions to the wetter, less elevated and convergent parts of the landscape. The same down-slope trend was observed for topsoil pH, available Mg, and available K. However, within the middle part of the landscape the means of the drier, divergent slope positions (Middle-D unit) were very similar to those of the wetter, convergent slope positions (Middle-C unit) with respect to these target properties. Hence, no across-slope trend in these target properties was evident. In contrast, macroporosity decreased down- and across slope. Total C generally deceased down-slope also but increased across-slope from divergent to convergent positions.

5.3.4.2 Soil-landscape units

The relationships between the target properties and the soil-landscape units are examined by considering the differences in the target property means of these units in both plots (Table 5.5).

Table 5.5. Mean target property values of the soil-landscape units in both plots. Means followed by the same letter are not significantly different ($P < 0.05$).

Property†	**Plot‡**	**Soil-landscape units**	
		Dry	**Wet**
Topsoil pH	Pre	4.77 a	5.16 c
	Post	4.74 a	4.96 b
Mg (cmol$_c$/kg)[1]	Pre	2.01 a	4.28 d
	Post	2.40 b	2.84 c
P (ppm)[1]	Pre	9.52 a	17.09 b
	Post	14.63 b	25.11 c
K (cmol$_c$/kg)	Pre	0.34 a	0.56 bc
	Post	0.52 b	0.64 c
MP (%)	Pre	15.23 a	9.37 b
	Post	9.91 b	7.70 b
TC (%)	Pre	3.79 a	3.39 a
	Post	4.95 b	4.53 b

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § Dry = dry soil-landscape unit, Wet = wet soil-landscape unit (defined in Chapter 4, section 4.3.3.2).

[1] Geometric means presented.

Relationships in the pre-harvested plot

For all target properties except total C, the means of the Dry soil-landscape unit were significantly ($P < 0.001$) different from those of the Wet soil-landscape unit in the pre-harvested plot (Table 5.5). The data show that the Dry unit was more acidic (lower topsoil pH), had lower levels of available nutrients (Mg, P, and K), and had greater macroporosity than the Wet unit. Both soil-landscape units had similar mean total C values. The management-related differences between the Wet and Dry units in the pre-harvested plot correspond exactly to those already described between the Wet and Dry broad drainage classes (section 5.3.2.2). The soil-landscape units behave similarly to the broad drainage classes because they were defined according to the dominance of one or other of the broad drainage classes. That is, the Wet soil-landscape unit is dominated by Wet soils whereas the Dry soil-landscape unit is dominated by Dry soils (Chapter 4, section 4.3.3.2).

Relationships in the post-harvested plot: the impacts of harvesting

Statistically, forest harvesting had only a limited affect on the relationships between the target properties and the soil-landscape units. The means of the Dry soil-landscape unit were significantly ($P < 0.05$) different from those of the Wet soil-landscape unit for most target properties (topsoil pH, available Mg, P, and K) after forest harvesting (Table 5.5). Despite the significant ($P < 0.01$) post-harvesting reduction in the mean topsoil pH and available Mg values of the Wet unit, the Dry unit continued to be more acidic and lower in available nutrients (Mg, P, and K). However, the mean macroporosity of the Dry unit was significantly ($P < 0.001$) decreased after harvesting which resulted in the mean value of the Dry unit becoming similar to that of the Wet unit. The Wet and Dry units remained similar with respect to mean total C.

From a management perspective, forest harvesting has removed all differences between the soil-landscape units and consequently both units could be managed similarly with respect to all target properties after harvesting (Table 5.5). Harvesting significantly reduced the mean macroporosity of the Dry unit (9.9%) to a level just below or at the 10% management threshold whereas that of the Wet unit (7.7%) remained below the threshold. The mean available P of the Dry unit was significantly ($P < 0.001$) increased after harvesting to a level in excess of the 12 ppm management threshold whereas that of the Wet unit remained well above the threshold. Both soil-landscape units have medium concentrations of available Mg and available K (Blakemore *et al.*, 1987). Harvesting significantly ($P < 0.001$) increased the mean available K of the Dry unit from a low to a medium level whereas the mean available Mg of the Wet unit was significantly ($P < 0.001$) decreased from a high to a medium level after harvesting. The mean total C values of both units were significantly ($P < 0.001$) increased from low to medium levels after harvesting whereas mean topsoil pH remained low for both units.

5.3.4.3 Terrain attributes

The relationships (correlation) between the target properties and the terrain attributes are examined by considering the proportion of variation in the target properties explained by the multi-linear regression models and their constituent terrain attributes in both plots (Table 5.6).

Table 5.6. R^2 values (%) of the regression models and partial R^2 values (%) of their constituent terrain attributes.

		Terrain attributes§						
Property†	**Plot‡**	**Z**	β	Ψ	$\mathbf{K_{pl}}$	$\mathbf{Z_r}$	W	**Model**
Topsoil pH	Pre	31.4	-	-	5.1	-	-	36.5
	Post	6.5	-	-	-	26.4	-	32.9
Mg (cmol$_c$/kg)	Pre	59.0	-	-	-	-	-	59.0
	Post	-	3.9	-	-	6.2	3.9	14.1
P (ppm)	Pre	26.5	-	9.7	4.1	-	-	40.2
	Post	-	12.0	5.4	-	10.6	-	28.0
K (cmol$_c$/kg)	Pre	22.5	-	-	-	-	-	22.5
	Post	-	-	-	-	14.4	-	14.4
MP (%)	Pre	16.2	11.6	-	-	-	-	27.8
	Post	-	-	-	-	-	-	-
TC (%)	Pre	-	-	-	-	6.7	-	6.7
	Post	-	9.4	-	-	7.4	-	16.8

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § **Z** = elevation, β = slope steepness, Ψ = aspect, $\mathbf{K_{pl}}$ = plan curvature, $\mathbf{Z_r}$ = relative elevation, W = topographic wetness index, **Model** = multi-linear regression models.

Not all terrain attributes were found to be ($P < 0.01$) correlated to the target properties. For instance, profile curvature and total curvature were not significantly correlated to any target property in either plot and were not used in the multi-linear regression models as a consequence. Most target properties were significantly correlated to only a few attributes at most.

Relationships in the pre-harvested plot

The multi-linear regression (MLR) models explained between about 20 and 40% of the variation in most target properties (topsoil pH, available P available K, and macroporosity) in the pre-harvested plot, indicating that the correlation between these properties and the terrain attributes was fairly weak (Table 5.6). The most strongly correlated target property was available Mg, with the MLR model for this property explaining almost 60% of the variation. In contrast, the MLR model for total C explained only about 7% of the variation in this property. Thus, total C was the least strongly correlated target property. The generally weak correlation between the terrain attributes and most target properties in the pre-harvested plot could be attributed to a combination of several factors including the non-liner relationship between some target properties and terrain attributes and the estimation of the sample point locations.

The data in Table 5.6 show that all target properties in the pre-harvested plot, except total C, are most strongly correlated to elevation (Z). Elevation explained between 16 and 31% of the variation in most target properties and nearly 60% of the variation in available Mg. Total C was the only target property found not to be correlated to elevation (weakly correlated to relative elevation instead). Although available P was most strongly correlated to elevation, aspect and plan curvature also explained some of the variation in this property. Plan curvature and slope steepness also accounted for some of the variability in topsoil pH and macroporosity respectively. Almost half of the variation in macroporosity explained by the MLR model for that property could be attributed to slope steepness. Available Mg and K were correlated to elevation alone.

Relationships in the post-harvested plot: the impacts of harvesting

In the post-harvested plot, the MLR models explained between 14 and 33% of the variation in most target properties (Table 5.6), which suggests that forest harvesting has generally weakened the correlation between the terrain attributes and the target properties. The proportion of variation explained by the MLR models was lower after harvesting for all target properties except total C (for which the proportion explained increased). In the extreme case, no terrain attributes were found to be significantly ($P < 0.01$) related to macroporosity after harvesting meaning that a MLR model could not be developed for this property in the post-harvested plot.

The terrain attribute most strongly correlated to the majority of target properties in the post-harvested plot was relative elevation (Z_r). Relative elevation explained between 6 and 26% of the variation in most target properties. In contrast to the pre-harvested plot, elevation was correlated only to topsoil pH and it explained a relatively small proportion of the variation in that property. Available P was most strongly correlated to slope steepness but was also correlated to relative elevation and aspect. Although available Mg was most strongly correlated to relative elevation, topographic wetness index and slope steepness also explained some of the variation in this property.

The terrain-attribute target-property relationships in the post-harvested plot differ from those in the pre-harvested plot. Forest harvesting may be responsible for some of the differences but it is likely that the difference in landscape hydrology between the plots (Chapter 4, section 4.3.2.4) is largely responsible. The hanging nature of the sub-catchment within the post-harvested plot may explain the lack of correlation between elevation and the target properties – the potentially strong hydraulic gradients throughout the post-harvested sub-catchment may mean that the soils do not progressively and uniformly become wetter (or higher in nutrients and lower in macroporosity as a consequence) with decreasing elevation as they appear to do in the pre-harvested plot. However, relative elevation exhibits some control over the target property values in the post-harvested plot because this attribute predicts soil wetness based on the elevation of the landforms in the immediate vicinity of the sample points. Therefore, the relationship to relative elevation is not as influenced by the landscape outside the plot boundaries as is the relationship to elevation. The importance of (relative) landscape position as a driver of differences in soil wetness and, consequently, the target property values, is highlighted by the dominance of the two elevation-related terrain attributes in explaining the variation of the target properties in both plots.

5.4 Summary and conclusions

Forest harvesting was found to have had a significant affect on the magnitude of all target properties. The means of some target properties (topsoil pH, available Mg, and macroporosity) were significantly decreased whereas the means of other target properties (available P, available K, and total C) were significantly increased after harvesting. The harvesting activities likely to be responsible for the observed affects on the target property means include (1) deposition of organic material (slash), (2) harvesting vehicle trafficking, and (3) land-cover change from mature forest to grassland. The only harvesting effect likely to require a management response was the significant reduction in macroporosity from an adequate to an inadequate level.

The variance of some target properties was also found to have been significantly affected by forest harvesting. The variance of topsoil pH and available Mg was significantly decreased whereas the variance of total C was significantly increased after harvesting. The patchy nature of slash deposition probably led to the increased variance of total C whereas the change from forest to more uniform grassland vegetation may have reduced the variance of topsoil pH and available Mg. The increased variance of total C probably reduced the accuracy with which this property could be spatially predicted (Chapter 6).

Most target properties were generally strongly related to the modified soil drainage classes and the landscape units in the pre-harvested plot. Two distinct groupings of classes/units were evident. For most target properties the Well and Imperfectly Drained soils (Upper and Middle-H units), had similar means and both were significantly different from those of the Somewhat Poorly and Poorly Drained soils (Middle-L and Lower units) which tended to be similar. The distinction between the two groups of classes/units also reflected a forest management difference with respect to some target properties (available P, available K, and macroporosity). The means of most target properties (topsoil pH, available Mg, available P, and available K) generally increased down-slope from the drier, more elevated landscape positions to the wetter, less elevated positions and as the soil drainage became more impeded. The patterns of relationships between the target properties and the modified drainage classes were similar to those between the target properties and the landscape units because the modified drainage classes are themselves fairly strongly related to the landscape units in the pre-harvested plot.

Forest harvesting altered and weakened the relationships between most target properties and the modified soil drainage classes and landscape units by altering the means of some classes/units. Fewer differences in mean values between the classes/units in the post-harvested plot than in the pre-harvested plot are indicative of the weaker relationships. After harvesting, the relationships between the target properties and the modified drainage classes were weaker for all target properties except topsoil pH (made stronger) whereas the relationships between the target properties and the landscape units were weaker for all target properties except total C (made stronger). For some target properties (available P, available K, and macroporosity) the means of the Well and Imperfectly Drained soils were significantly affected by harvesting because these soils occur in upper landscape positions where harvesting disturbance was concentrated. With respect to available Mg and topsoil pH, the means of the Somewhat Poorly Drained soils were significantly affected by harvesting. After harvesting, all modified drainage classes could be managed similarly for all target properties except macroporosity and all landscape units could be managed similarly for all target properties except macroporosity and available K. The soil drainage- and landscape-related trends observed in the pre-harvested plot were essentially the same in the post-harvested plot.

In the pre-harvested plot, most target properties were strongly related to the broad soil drainage classes and the soil-landscape units. The Dry class/soil-landscape unit was significantly more acidic, had lower levels of available nutrients (Mg, P, and K) and greater macroporosity than the Wet class/soil-landscape unit. Moreover, the two classes/soil-landscape units could be managed differently with respect to available P, available K, and macroporosity. The soil-landscape units behave similarly to the broad drainage classes because the Wet soil-landscape unit is dominated by Wet soils whereas the Dry soil-landscape unit is dominated by Dry soils.

The relationships between most target properties and the broad drainage classes and soil-landscape units were not altered or weakened by forest harvesting. However, the means of some classes/units were altered by forest harvesting. After harvesting, the relationships between the target properties and the broad drainage classes remained unchanged for all target properties except available Mg and K (made weaker) whereas the relationships between the target properties and the soil-landscape units remained unchanged for all target properties except macroporosity (made weaker). Thus, the broad drainage classes and soil-landscape units were generally less affected by forest harvesting in terms of the target properties than were the modified drainage classes and the landscape units. Harvesting resulted in the mean value of the Wet class becoming more like that of the Dry class with respect to available Mg and vice versa with respect to available K. The mean macroporosity of the Dry soil-landscape unit became more like that of the Wet unit after harvesting. After harvesting, both broad drainage classes could be managed similarly for all target properties except macroporosity (adequate in the Dry soils, inadequate in the Wet) whereas both soil-landscape units could be managed similarly for all target properties.

The correlation between the target properties and the terrain attributes was fairly weak in the pre-harvested plot with the multi-linear regression models explaining between 20 and 60% of the variation in most target properties. Available Mg was the most strongly correlated target property whereas total C was the least strongly correlated. All target properties except total C were most strongly correlated to elevation. However, aspect, plan curvature, relative elevation, and slope steepness were also correlated to some target properties. Forest harvesting generally weakened the correlation between the target properties and the terrain attributes. The proportion of the variation explained by the multi-linear regression models was lower for all target properties except total C after harvesting. Also, relative elevation surpassed elevation as the terrain attribute most strongly correlated to the majority of target properties after harvesting. The nature of the landscape hydrology of the post-harvested plot is probably responsible for relative elevation being a more important determinant of the target properties than elevation.

The soil drainage classes presently used in New Zealand were modified by separating the existing imperfectly drained soils into two classes (Imperfectly Drained and Somewhat Poorly Drained) on the basis of a difference in soil profile hydromorphology observed predominantly within Mottled Yellow Ultic Soils. The separation was found to be appropriate and effective because, in the pre-harvested plot, the means of the Imperfectly Drained soils were significantly different from those of the Somewhat Poorly Drained soils for all target properties except total C. Moreover, the two classes could be managed differently with respect to available P, Mg, and K. It is recommended that the New Zealand soil drainage criteria be modified by placing greater emphasis on the abundance of and depth to redox depletions within the profile. The difference in drainage class within the Mottled Yellow Ultic subgroup could be communicated at the soilform level if the revised soil drainage criteria were incorporated into the soilform (replacing the permeability classes).

Based on the results of this study it is concluded that:

1. Forest harvesting significantly altered the magnitude of all target soil properties and the variance of some target soil properties.

2. Forest harvesting altered and weakened the relationships between most target soil properties and the modified soil drainage classes, landscape units, and terrain attributes. However, forest harvesting did not alter or weaken the relationships between most target soil properties and the broad soil drainage classes and soil-landscape units in southern Mahurangi Forest.

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CHAPTER SIX

Spatial prediction of soil properties: impacts of forest harvesting on a range of prediction techniques

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6.1 Introduction

The movement of New Zealand's forestry industry towards sustainable and site-specific forest management has created new and specific demands for forest soil information. Quantitative, precise, and detailed information on the magnitude and variability of certain target soil properties (i.e. key soil indicators of sustainable forestry), in addition to accurate information regarding the spatial distribution of locally significant soil classes (e.g. drainage classes), is essential for assessing and monitoring forest site quality and for implementing site-specific forest management programmes (Payn and Thwaites, 1998; Turner *et al.*, 1999; Payn *et al.*, 1999, 2000; Fox, 2000; Shaw and Carter, 2002). There is also a commercial desire for this soil information to be collected in a cost-effective manner and presented in easily accessible, flexible formats (Payn and Thwaites, 1998).

Most existing soil property information relating to New Zealand's forest estates is inadequate, being generally too sparse for the comprehensive assessment of forest site quality and the implementation of site-specific forest management (Payn and Thwaites, 1998; Payn *et al.*, 1999, 2000). Therefore, the required target soil property information must be collected before sustainable and site-specific forest management can be achieved (Payn *et al.*, 1999).

Although it is now widely recognised that conventional soil survey is unable to adequately provide the required detailed soil information (McKenzie and Austin, 1993; Moore *et al.*, 1993; Payn and Thwaites, 1998; Thwaites and Slater, 2000), the most suitable approach to predicting and mapping the spatial distribution of target soil properties in plantation forest environments has not yet been clearly established. However, quantitative soil-landscape modelling has been highlighted as a potentially useful tool for this purpose (Jones, 1998; Payn and Thwaites, 1998; McKenzie and Ryan, 1999; Thwaites and Slater, 2000). When used in association with pedometrics and spatial information technology (e.g. GIS), quantitative soil-landscape modelling has the potential to provide the required target soil property information in appropriate formats (e.g. Payn and Thwaites, 1998; Thwaites and Slater, 2000; Schmidt, 2002). Furthermore, the quantitative soil-landscape modelling approach may be cost effective because it predicts soil property distribution from readily available and relatively cheap ancillary (explanatory) landscape information (Hewitt, 1993), such as digital elevation data. Pedometric tools for mapping target soil properties such as geostatistical interpolation (usually via kriging) techniques have generally been shown to be effective in intensively sampled areas or where there is relatively strong spatial dependence (e.g. Kravchenko, 2003). However, the potentially large number of samples required to achieve an adequate level of prediction accuracy across large forest estates may make this approach excessively costly (McKenzie and Austin, 1993; Kravchenko, 2003).

The quantitative soil-landscape modelling approach to the spatial prediction of target soil properties has generally been found to perform well in agricultural and range-land environments (e.g. Odeh *et al.*, 1995; Bishop and McBratney, 2001) and its potential usefulness within plantation forest environments has been recognised (McKenzie and Ryan, 1999; Thwaites and Slater, 2000). However, the suitability of quantitative soil-landscape modelling to plantation forest environments has not yet been comprehensively evaluated. Forest land-management activities such as clear-fell harvesting can cause considerable soil disturbance (Simard *et al.*, 2001; Palmer *et al.*, 2004) and have been shown to significantly alter the magnitude of soil properties in both New Zealand (e.g. Parfitt *et al.*, 2002) and elsewhere (e.g. Simard *et al.*, 2001). Therefore, the soil-landscape relationships used by quantitative soil-landscape models to predict the spatial distribution of target soil properties may be altered or weakened by forest harvesting (Block *et al.*, 2002) which, in turn, may reduce the predictive performance of quantitative soil-landscape models. However, the impacts of forest harvesting on soil-landscape relationships and the predictive performance of quantitative soil-landscape modelling had not been investigated. Nor had the impacts of forest harvesting on the performance of other approaches to the spatial prediction of target soil properties (e.g. class-based or geostatistical prediction techniques) been determined. Gaining an understanding of the impacts of forest harvesting on the predictive performance of quantitative soil-landscape models (among other approaches) is therefore a crucial step towards the comprehensive evaluation of their suitability to plantation forest environments.

This chapter reports on a study conducted as part of a wider investigation into the impacts of hauler-based, clear fell, forest harvesting on the performance of soil-landscape modelling as a tool for the spatial prediction of soil classes and target soil properties in a radiata pine forest. The research was conducted within southern Mahurangi Forest, an exotic, *Pinus radiata*-dominated plantation forest, situated on the Northland Peninsula, North Island, New Zealand. The objective of this study was to determine and compare the impacts of hauler-based, clear-fell, forest harvesting on the performance of seven techniques representing the class-based, quantitative soil-landscape modelling, and geostatistical approaches to the spatial prediction of target soil properties.

In total, seven individual prediction techniques were investigated: (1) class-based 1 (CB1), (2) class-based 2 (CB2), (3) class-based 3 (CB3), (4) class-based 4 (CB4), (5) multi-linear regression (MLR), (6) regression kriging (RK), and (7) ordinary kriging (OK). Techniques 1-4 represent the class-based approach; techniques 5-6 are quantitative soil-landscape models; and technique 7 is the sole representative of the geostatistical approach. Three of the techniques actually lie at interfaces of the broad approaches: the CB2 and CB4 techniques relate both to the class-based and soil-landscape modelling approaches (semi-quantitative soil-landscape models), and the RK technique relates both to the soil-landscape modelling and geostatistical approaches. The quantitative soil-landscape modelling and geostatistical techniques selected have been commonly used for soil property prediction (e.g. ordinary kriging) or are considered to be among the most successful of their type (e.g. regression kriging) within agricultural environments (Voltz and Webster, 1990; Odeh *et al.*, 1994, 1995; Brus *et al.*, 1996; Chaplot *et al.*, 2000; Lagacherie and Voltz, 2000; Utset *et al.*, 2000; Bishop and McBratney, 2001; Schloeder *et al.*, 2001; Triantafilis *et al.*, 2001). The class-based techniques represent a more traditional approach to soil property prediction.

For the purposes of this study, six target soil properties were measured and predicted: (1) topsoil pH, (2) available P, (3) available Mg, (4) available K, (5) macroporosity, and (6) total C. From this point on, the target soil properties shall collectively be referred to as 'the target properties'.

6.2 Methodology

The methods used to establish the sampling plots, sample the soils, measure the target properties, determine the terrain attributes, and perform the preliminary data analysis in this study have already been described in previous chapters. Rather than repeating these, the reader is referred to the following sections: methods of plot establishment, section 4.2.4 (Chapter 4); methods of soil sampling and observation, section 5.2.1 (Chapter 5); methods of soil analysis, section 5.2.2 (Chapter 5); methods of terrain analysis, section 5.2.3 (Chapter 5); methods of preliminary data analysis, section 5.2.3.1 (Chapter 5). A comprehensive description of the study site location and environment was given in Chapter 3.

The methods of statistical analysis used in the making and evaluating the target property predictions are given below.

6.2.1 Statistical analysis

All statistical analyses were performed using SAS/STAT version 8 (SAS Institute, 2000) and MICROSOFT EXCEL version 2002 (Microsoft Corporation, 2002). Target property variances in the validation data sets were compared using an F probability distribution test.

6.2.1.1 Making target property predictions

The class-based techniques (CB1, CB2, CB3, and CB4) used either: soil drainage classes (modified and broad), landscape units, or soil-landscape units (a combination of drainage classes and landscape units) as the basis for prediction whereas MLR and RK used quantitative soil-landscape relationships. The OK technique is a purely geostatistical technique based on the semi-variogram. The arithmetic mean of the development data (the sample mean) was also calculated to provide a reference technique (REF) against which the other techniques could be compared. A useful prediction technique should provide substantially better predictions than sample means.

Development and validation data sets

Within each plot, the models (relationships or rules) for making the target property predictions were developed according to the various prediction techniques using only a proportion (approximately 70%) of the total number of data points (the development set). A development set, consisting of 146 randomly selected data points, was established for each plot and was used by all prediction techniques within a given plot. The procedure for randomly selecting a development set was performed on each plot separately. Therefore, the data point identification numbers of the development set in the pre-harvested plot were different from those in the post-harvested plot. The development sets were selected by generating a set of random numbers, one for each of the 208 data points in a plot. The data points were then ranked according to the corresponding random numbers (from the largest random number to the smallest). The first 146 data points on the resulting list were assigned to the development set. The remaining 62 data points were assigned to the validation set and were not used for model development.

Class-based prediction techniques

The class-based techniques simply involved grouping the development set data according to soil drainage class (modified and broad), landscape unit, or soil-landscape unit and then calculating the least squares mean value of each target property for each class or unit. CB1 used directly observed broad soil drainage classes (two classes: Wet soils and Dry soils) whereas CB2 used predicted broad drainage classes (i.e. the soil-landscape units of the qualitative soil-landscape models — Chapter 4). The CB3 technique used directly observed modified soil drainage classes (four classes: Well Drained, Imperfectly Drained, Somewhat Poorly Drained, and Poorly Drained) whereas CB4 used the landscape units of the qualitative soil-landscape models. The CB2 and CB4 techniques are effectively semi-quantitative soil-landscape models. Therefore, they represent both the soil-landscape modelling and class-based approaches to target property prediction. Essentially, CB2 represents the traditional soil survey approach to target property prediction — the calculation of a mean target property value for each soil-landscape unit and its extrapolation using a soil-landscape unit map.

Quantitative soil-landscape modelling techniques

The two quantitative soil-landscape modelling techniques involved the regression of the terrain attributes with the target property values at the development points. The regression was performed using stepwise, least squares, multi-linear regression. Only those terrain attributes that were significantly ($P < 0.01$) correlated to the target property in question were retained for use in the regression model.

The MLR technique involved the calculation of regression equations describing the relationships between the target properties and the terrain attributes. The regression equations can be expressed in matrix form as:

$$z(si) = a + \mathbf{X}b + \varepsilon$$

where $z(si)$ represents the measured target property values at the development points ($i = 1,\ldots,n$), **X** is the $p \times n$ matrix of terrain attributes (predictor variables, p) at each development point, and ε is the error term (which has constant variance and zero mean). The regression coefficients, represented by a and b, are constants (Odeh *et al.*, 1994).

The RK technique (regression kriging model C of Odeh *et al.*, 1995) involved adding the predictions made by the MLR technique at the validation points to the residual (error) values associated with the MLR predictions (calculated at the development points and then interpolated to the validation points using ordinary kriging). The target property predictions (z*), made using RK, were calculated at the validation points (*sj*) using:

$$z^*(sj) = zpr^* + \varepsilon^*$$

where *zpr** represents the MLR predictions of the target property values and ε^* represents the kriged MLR residuals at the validation points (Odeh *et al.*, 1995). The RK technique is an example of a hybrid quantitative soil-landscape modelling prediction technique, so-called because it represents a combination of statistical and geostatistical techniques.

Geostatistical prediction (ordinary kriging)

Target property predictions were made using OK according to the following procedure. Experimental semi-variograms were generated from the development set data and theoretical curves were then fitted to represent that data. All theoretical curves fitted were either Spherical or Gaussian. The parameters of the fitted theoretical curves were then used to provide the weighting for the kriging interpolation procedure. Rather than making predictions from a known soil class or other explanatory or ancillary data (e.g. the terrain attributes), the kriging approach predicts target property values at unknown points by making use of the weighted average of known values at surrounding points and the principle that the values of a target property at near points are more similar than those at points further away. Ordinary kriging estimates the weighted average of a target property at an (unvisited) validation point, z*(*sj*), according to the following:

$$z^*(sj) = \sum_{i=1}^{n} \lambda_i z(si)$$

where λ_i are the weights given to each of the *n* development points and z(*si*) represents the target property values measured at the development points. An unbiased estimation is achieved because the weights sum to unity (Odeh *et al.*, 1994; Schloeder *et al.*, 2001).

Application and validation of the prediction techniques

The prediction techniques (more correctly, the models developed using those techniques) were then applied to make target property predictions at the 62 validation data points in each plot. The class-based techniques were applied by assigning the appropriate mean value (calculated for each class or unit) to the corresponding (known) class or unit at a given validation point. The application of the quantitative soil-landscape modelling techniques involved using the regression equations, derived from the development data, at the validation points (where the terrain attribute values were known) to predict the target property values. In the case of the RK technique, application also involved the interpolation of the errors from the development points (resulting from the MLR predictions) to the validation points. The geostatistical technique was automatically applied in the process of interpolating the target property values from the development points to the validation points.

The performance of the prediction techniques were evaluated (validated) by determining how close the predicted target property values were to the observed (measured) at each validation point (section 6.2.1.2). The prediction techniques were then compared within and between plots in terms of their (relative) prediction performance.

6.2.1.2 Comparison and evaluation of prediction techniques

Bias and accuracy

Mean error (ME) and root-mean-square error (RMSE) (defined in Voltz and Webster, 1990; Triantafilis *et al.*, 2001) were used to assess the bias and the accuracy of the prediction techniques, respectively. Both measures were calculated from the observed (z) and predicted (z^*) values at the 62 (l) validation points (sj). The ME was determined using the equation:

$$\text{ME} = \frac{1}{l}\sum\left[z(s_j) - z^*(s_j)\right]$$

The ME should be close to zero for unbiased predictions (Odeh *et al.*, 1994; Triantafilis *et al.*, 2001). Negative ME values indicate that the prediction technique is over-estimating the target property in question whereas positive ME values indicate under-estimation (Triantafilis *et al.*, 2001). The RMSE was calculated using:

$$\mathrm{RMSE} = \left\{ \frac{1}{l} \sum_{j=1}^{l} \left[z(s_j) - z^*(s_j) \right]^2 \right\}^{0.5}$$

The lower the RMSE value, the more precise the predictions are (Odeh *et al.*, 1994; Triantafilis *et al.*, 2001).

A relative measure of accuracy, known as the goodness-of-prediction (G) value (Agterberg, 1984; Schloeder *et al.*, 2001), was also used. G is a measure of how much more (or less) accurate a given technique is relative to the accuracy of the sample mean (REF). G was calculated using:

$$\mathrm{G} = \left(1 - \left\{ \sum_{j=1}^{l} \left[z(s_j) - z^*(s_j) \right]^2 / \sum_{j=1}^{l} \left[z(s_j) - \bar{z} \right]^2 \right\} \right) \times 100$$

where $\bar{z}$ is the sample mean (Schloeder *et al.*, 2001). A positive G value indicates an improvement over the sample mean whereas a negative G value indicates that the technique in question performed worse than the sample mean. The greater the G value, the greater the improvement in accuracy over that of the sample mean. A perfect prediction technique (with a RMSE of zero) would give a G value of 100% (Gotway *et al.*, 1996).

The values of RMSE and ME can be affected by large noise-to-signal ratios resulting from outliers in the data or by variation in noise-to-signal ratios between the target properties (Odeh *et al.*, 1994; Triantafilis *et al.*, 2001). Therefore, RMSE and ME may not be completely reliable and consistent measures by which to compare the prediction techniques. An assessment of the relative performance of the techniques required the use some additional measures.

Relative performance

Two more robust measures of performance, based on the ranking of prediction techniques, were suggested by Laslett *et al.* (1987): (1) mean rank (MR) and (2) standard deviation of rank (SDR). The relative performance of the prediction techniques was assessed using MR and SDR. The rank of each prediction technique was determined for each validation data point (r_{ij}) on the basis of the squared error of the prediction (Odeh *et al.*, 1994; Triantafilis *et al.*, 2001). The technique with the lowest squared error (the closest prediction) was given a rank of 1 and the technique with the largest squared error was assigned the highest rank. On the basis of the rank information, the MR of the *i*th technique was calculated for a given target property by:

$$\mathrm{MR} = \frac{1}{n}\left[\sum_{i=1}^{n} r_{ij}\right]$$

and the SDR of the *i*th technique was calculated using:

$$\mathrm{SDR} = \left[\frac{1}{n-1}\sum_{j=1}^{n}\left(r_{ij} - \mathrm{MR}\right)^{2}\right]^{0.5}$$

The technique with the lowest MR (the most accurate) and lowest SDR (the most consistent) is considered to be the best (Odeh *et al.*, 1994). A single value that takes both the MR and SDR into account was needed to clearly determine the relative performance of the techniques. The value was calculated by adding the MR to the SDR. The technique with the lowest MR+SDR value was the best performer.

6.3 Results and discussion

6.3.1 Summary statistics

The data used to make the target property predictions, according to the various prediction techniques described above, are summarised by the statistics given in Table 6.1.

Table 6.1. Summary statistics of target property data comprising the development sets of both plots. Variance values followed by the same letter are not significantly different ($P < 0.05$).

Property†	Plot‡	Statistic				
		Mean	Median	Variance	Minimum	Maximum
Topsoil pH	Pre	4.96	4.91	0.13 a	4.38	6.53
	Post	4.78	4.78	0.08 b	3.76	5.62
Mg (cmol$_c$/kg)*	Pre	1.07	1.05	0.28 a	-0.29	2.20
	Post	0.91	0.92	0.13 b	-0.25	1.89
P (ppm)*	Pre	2.54	2.44	0.36 a	1.33	4.68
	Post	2.79	2.75	0.35 a	0.19	4.14
K (cmol$_c$/kg)*	Pre	0.65	0.66	0.03 a	0.00	1.05
	Post	0.72	0.69	0.02 a	0.37	1.16
MP (%)*	Pre	3.25	3.12	1.82 a	0.00	6.40
	Post	2.83	2.82	1.48 a	0.00	5.81
TC (%)	Pre	3.59	3.50	1.57 a	0.85	9.43
	Post	4.87	4.77	2.28 b	1.06	15.90

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested.

* Summary statistics of transformed data presented.

The effects of forest harvesting on the target property means and variances (adjusted for modified soil drainage classes) were described and discussed in Chapter 5. It was shown that forest harvesting had a significant affect on the variance of some target properties: topsoil pH, and available Mg were found to be significantly ($P < 0.05$) less variable whereas total C was significantly ($P < 0.01$) more variable after harvesting (Chapter 5, section 5.3.1.1). Although the summary statistics presented in Table 6.1 were not adjusted for drainage class (i.e.

they include the effect of drainage class), the differences in target property variance between the plots were similar to those described in Chapter 5.

The target property data of the validation sets are summarised in Table 6.2. Note should be taken of the difference in target property variances between the plots because, for some target properties, it is relevant to the examination of the impact of forest harvesting on prediction accuracy and relative performance. The difference in the variance of topsoil pH found between the plots within the development data sets was not repeated in the validation data sets.

Table 6.2. Summary statistics of target property data comprising the validation sets of both plots. Variance values followed by the same letter are not significantly different ($P < 0.01$).

		Statistic				
Property†	**Plot‡**	**Mean**	**Median**	**Variance**	**Minimum**	**Maximum**
Topsoil pH	Pre	4.92	4.87	0.07 a	4.41	5.82
	Post	4.77	4.77	0.08 a	4.11	5.38
Mg (cmol$_c$/kg)*	Pre	1.12	1.09	0.26 a	0.19	2.15
	Post	0.89	0.87	0.13 b	-0.12	1.83
P (ppm)*	Pre	2.57	2.53	0.38 a	1.46	4.20
	Post	2.75	2.65	0.28 a	1.74	4.11
K (cmol$_c$/kg)*	Pre	0.66	0.66	0.02 a	0.31	0.99
	Post	0.72	0.73	0.02 a	0.36	1.05
MP (%)*	Pre	3.69	3.41	1.42 a	1.62	6.72
	Post	2.87	2.84	1.55 a	0.00	5.95
TC (%)	Pre	3.61	3.51	0.90 a	1.66	5.92
	Post	5.08	4.77	4.09 b	2.10	16.19

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested.

* Summary statistics of transformed data presented.

With respect to the validation data (Table 6.2), the variances of topsoil pH, available P, available K, and macroporosity were similar in both plots. However, there were significant ($P < 0.01$) differences between the plots in terms of the variances of available Mg (two times greater in the pre-harvested plot than in the post-harvested) and total C (more than four times greater in the post-harvested plot than in the pre-harvested).

It was observed in the field that the deposition of slash and the removal of litter and topsoil in the post-harvested plot – as a result of forest harvesting activity – had occurred in an uneven manner. Thus, the distribution of slash, litter, and topsoil was somewhat patchy in nature throughout the post-harvested plot. The patchy distribution of these carbon sources may explain the marked increase in the variance of total C after harvesting. It is more difficult to directly attribute the reduction in the variance of available Mg to forest harvesting but perhaps it is due to the change in vegetation cover and the associated change to soil nutrient dynamics (Parfitt *et al.*, 2002).

The mean predicted target property values together with the mean observed ('true') values of the validation sets of both plots are presented in Table 6.3. Tables containing the full set of statistics summarising the predictions are given in Appendix Three.

Table 6.3. Mean predicted and observed target property values at the validation points of both plots.

		Prediction technique§								
Property†	**Plot‡**	**OBS**	**CB1**	**CB2**	**CB3**	**CB4**	**MLR**	**RK**	**OK**	**REF**
Topsoil pH	Pre	4.92	4.95	4.96	4.95	4.97	4.95	4.95	4.92	4.96
	Post	4.77	4.75	4.78	4.76	4.77	4.77	4.76	4.77	4.78
Mg (cmol_c/kg)[1]	Pre	3.05	2.86	2.90	2.86	2.90	2.86	2.81	2.81	2.92
	Post	2.43	2.44	2.48	2.45	2.45	2.44	-	2.48	2.49
P (ppm)[1]	Pre	13.13	12.47	12.64	12.39	12.96	12.27	12.05	12.13	12.71
	Post	15.70	15.34	16.24	15.53	16.00	16.14	15.84	15.32	16.29
K (cmol_c/kg)	Pre	0.46	0.42	0.42	0.42	0.42	0.42	0.44	0.44	0.42
	Post	0.55	0.52	0.52	0.52	0.52	0.52	0.52	0.53	0.52
MP (%)	Pre	15.01	11.19	10.78	11.05	10.80	11.43	11.63	11.11	10.42
	Post	9.74	8.43	8.03	8.42	8.44	-	-	8.66	7.89
TC (%)	Pre	3.61	3.60	3.60	3.58	3.59	3.59	3.57	3.56	3.59
	Post	5.08	4.92	4.87	4.93	4.92	4.93	4.84	4.78	4.87

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § OBS = observed mean, CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique. [1] Geometric means presented.

For most target properties in both plots the mean predicted values were similar to the observed as would be expected from the means of predictions made from a large number of surrounding data points (development sets). The differences between predicted and observed means appeared greatest for macroporosity, particularly in the pre-harvested plot. Furthermore, all prediction techniques gave similar mean predictions for most target properties in both plots.

Note that the missing MLR and RK predictions of macroporosity in the post-harvested plot occurred because there were no sufficiently strong relationships between the terrain attributes and macroporosity in that plot. Therefore, neither the MLR nor RK techniques could be used to predict macroporosity because both make use of the relationships between the terrain attributes and the target properties (quantitative soil-landscape relationships). Note also that the missing RK prediction of available Mg in the post-harvested plot occurred because the theoretical semi-variogram of the MLR residuals could not be successfully estimated for that property in that plot.

6.3.2 Comparison and evaluation of prediction techniques

To compare and evaluate the performance of the prediction techniques and the effect of forest harvesting on them, the bias, accuracy, goodness-of-prediction, and relative performance (based on the analysis of rank) of the prediction techniques within and between plots were examined. The bias, accuracy, and goodness-of-prediction results are described first, followed by a description of the relative performance. The relative performance of the prediction techniques over all target properties was also examined.

6.3.2.1 Bias and accuracy

Prediction bias can be assessed by examining the mean error values of each prediction technique (Table 6.4).

Table 6.4. Mean error of target property predictions made in both plots.

		Prediction technique§							
Property†	**Plot‡**	**CB1**	**CB2**	**CB3**	**CB4**	**MLR**	**RK**	**OK**	**REF**
Topsoil pH	Pre	-0.028	-0.035	-0.030	-0.046	-0.030	-0.026	0.003	-0.039
	Post	0.013	-0.016	0.008	-0.002	-0.006	0.000	-0.009	-0.017
Mg	Pre	0.065	0.053	0.064	0.050	0.064	0.084	0.083	0.046
	Post	-0.003	-0.021	-0.008	-0.010	-0.006	-	-0.018	-0.022
P	Pre	0.051	0.038	0.057	0.013	0.067	0.085	0.079	0.033
	Post	0.024	-0.034	0.011	-0.019	-0.028	-0.009	0.025	-0.036
K	Pre	0.016	0.014	0.014	0.016	0.016	0.008	0.000	0.012
	Post	0.003	0.000	0.001	0.007	0.005	0.002	-0.001	-0.001
MP	Pre	0.405	0.434	0.430	0.438	0.386	0.380	0.420	0.462
	Post	-0.032	0.036	-0.022	-0.024	-	-	-0.045	0.057
TC	Pre	0.003	0.009	0.028	0.011	0.013	0.032	0.042	0.013
	Post	0.157	0.207	0.145	0.161	0.144	0.238	0.299	0.209

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § CB1 = class-based technique 1, CB2 =class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

All prediction techniques gave fairly unbiased ($-1 < ME < 1$) predictions of most target properties. Predictions of macroporosity in the pre-harvested plot and of total C in the post-harvested plot were generally the most biased with mean error values approximately an order of magnitude greater than the rest. For any given target property in either plot, all techniques were similarly unbiased with two notable exceptions: in the pre-harvested plot, OK gave considerably less biased predictions (by an order of magnitude) of both topsoil pH and available K than most other techniques. The predictions of most techniques were substantially less biased in the post-harvested plot for all target properties with the exception of total C (for which the predictions were considerably more biased in the post-harvested plot). Thus, the predicted values were focussed more centrally around the observed mean of the target property in question in the post-harvested plot. Negative mean error values indicate over-estimation (observed < predicted) whereas positive values indicate under-estimation (observed > predicted). The predictions of most techniques in the pre-harvested plot were under-estimates (for all target properties except pH) whereas the predictions of most techniques in the post-harvested plot were over-estimates (for all target properties except available K and total C).

The RMSE provides a measure of the accuracy of the prediction techniques (Table 6.5).

Table 6.5. Root-mean-square error of target property predictions made in both plots.

		Prediction technique§							
Property†	**Plot‡**	**CB1**	**CB2**	**CB3**	**CB4**	**MLR**	**RK**	**OK**	**REF**
Topsoil pH	Pre	0.234	0.209	0.237	0.219	0.225	0.220	0.215	0.264
	Post	0.252	0.252	0.245	0.251	0.227	0.227	0.242	0.277
Mg	Pre	0.463	0.380	0.464	0.381	0.422	0.358	0.328	0.504
	Post	0.348	0.346	0.340	0.362	0.369	-	0.339	0.365
P	Pre	0.550	0.565	0.553	0.573	0.586	0.576	0.536	0.609
	Post	0.505	0.516	0.517	0.516	0.513	0.510	0.486	0.522
K	Pre	0.148	0.136	0.150	0.135	0.131	0.125	0.123	0.146
	Post	0.154	0.146	0.153	0.141	0.139	0.136	0.143	0.157
MP	Pre	1.111	1.234	1.132	1.253	1.261	1.242	1.187	1.269
	Post	1.203	1.217	1.231	1.169	-	-	1.329	1.237
TC	Pre	0.915	0.910	0.963	0.892	0.858	0.777	0.806	0.943
	Post	2.013	1.979	2.047	1.908	1.837	1.891	1.919	2.016

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § CB1 = class-based technique 1, CB2 =class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Differences in RMSE between the target properties cannot be compared because the values of RMSE are influenced by factors such as the measurement scale of the data from which they were calculated. However, the accuracy of the prediction techniques can be compared within and between plots for a given target property.

The prediction accuracy of all techniques was similar for any given target property in either plot with the exception of available Mg in the pre-harvested plot where the RMSE ranged between 0.328 and 0.504. The similarity in accuracy of all prediction techniques found for most target properties in either plot indicates that, in general, the geostatistical and quantitative soil-landscape modelling techniques were not able to explain substantially more of the variability than the class-based techniques or the sample mean. Nevertheless, the geostatistical and quantitative soil-landscape modelling techniques (MLR, RK, and OK) tended to give slightly more precise predictions of most target properties than the other techniques. However, the prediction accuracy of the semi-quantitative soil-landscape modelling techniques (CB2 and CB4) was close to that of the geostatistical and quantitative soil-landscape modelling techniques for half the target properties in the pre-harvested plot (topsoil pH, available Mg, and available K) and one target property in the post-harvested plot (available K). Also, the prediction accuracy of the CB1 and CB3 techniques was relatively high for most target properties in the post-harvested plot and some target properties in the pre-harvested plot (available P and macroporosity). Moreover, the most precise predictions of macroporosity were given by the class-based techniques in both plots.

The geostatistical and quantitative soil-landscape modelling techniques may be able to give slightly more precise predictions because they are more sophisticated techniques that predict target properties from either quantitative and continuous explanatory variables (i.e. the terrain attributes) or detailed information about the spatial variability of the surrounding target property values (i.e. spatial dependence structure), or both. Therefore, they are generally able to better incorporate and account for the spatial variability of the target properties than are the other techniques. In contrast, the mean values of discrete classes and units used by the class-based techniques are generally less sensitive to within-class spatial variability and as such have a smoothing effect when making predictions. Although, the reasonably good predictive accuracy of the CB2 and CB4 techniques suggests that the semi-quantitative soil-landscape relationships (relating the target properties to soil-landscape units or landscape units) employed by these techniques account for a reasonable amount of the spatial variability in the target properties also. For example, the relatively wide range in the RMSE values of available Mg predictions in the pre-harvested plot occurred because this property was relatively strongly related to the terrain attributes, landscape units, and soil-landscape units and had a strong spatial dependence structure (Chapter 5). Thus, the geostatistical, quantitative soil-landscape modelling, and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques were able to give more precise predictions of available Mg than some of the other, less sophisticated, techniques (e.g. REF, CB3, and CB1) that were based on solely on soil drainage classes or the sample mean.

For most target properties, the predictions made using most techniques were slightly less precise in the post-harvested plot than in the pre-harvested. However, for available Mg and P the predictions made using most techniques were slightly more precise in the post-harvested plot. The significant ($P < 0.01$) reduction in the variance of available Mg after harvesting may, in part, explain the improved accuracy of available Mg predictions in the post-harvested plot. The fact that, in predicting available Mg, the accuracy of the REF technique improved by a greater margin than all other techniques after harvesting is further evidence that the reduction in the variance of available Mg is responsible for the improved prediction accuracy because variance is the main factor likely to influence the performance of the REF technique. Furthermore, the relationships between available Mg and the drainage classes (modified and broad), landscape units, soil-landscape units, and terrain attributes (Chapter 5, sections 5.3.2 and 5.3.4) were either weaker or unchanged after harvesting which means that the increased accuracy with which the class-based and quantitative soil-landscape modelling techniques predicted available Mg after harvesting was not the result of improved predictive relationships. Even though the difference in the variance of available P between the plots was not significant, it appears that the nominally lower variance in the post-harvested plot could be contributing to the increase in the accuracy of available P prediction after harvesting because the accuracy of the REF technique increased after harvesting by more than that of the other techniques. Also, the relationships between available P and the drainage classes (modified and broad), landscape units, soil-landscape units, and terrain attributes were either weaker or unchanged after harvesting (Chapter 5, sections 5.3.2 and 5.3.4) and so could not have contributed to the improved accuracy of the class-based and quantitative soil-landscape modelling techniques in the prediction of available P.

The poorer accuracy of the total C predictions in the post-harvested plot was probably due to the significant increase in the variance of total C after harvesting. It is possible that the weaker relationship between total C and the modified drainage classes after harvesting (Chapter 5, section 5.3.2.1) contributed to the reduction in the accuracy with which CB3 predicted total C in the post-harvested plot. However, there were no changes to the relationships between total C and the broad drainage classes or soil-landscape units after harvesting (Chapter 5, sections 5.3.2.2 and 5.3.4.2) which means that less precise predictions of total C made by CB1 and CB2 after harvesting cannot be explained by these relationships. The relationships between total C and the terrain attributes and landscape units were actually stronger in the post-harvested plot than in the pre-harvested (Chapter 5, sections 5.3.4.3 and 5.3.4.1). Therefore, the less precise predictions of total C given by CB4, MLR, and RK in the post-harvested plot cannot be attributed to weaker soil-landscape relationships.

Some techniques (CB1, CB3, and OK) gave less precise predictions of macroporosity in the post-harvested plot than in the pre-harvested. There was no significant difference in the variance of macroporosity between the plots. Therefore, factors other than variance are likely to have influenced the accuracy with which macroporosity was predicted. The weaker post-harvesting relationship between macroporosity and the modified drainage classes (Chapter 5, section 5.3.2.1) would explain the less precise prediction of macroporosity made by the CB3 technique after harvesting. However, the relationship between macroporosity and the broad drainage classes did not change after harvesting (Chapter 5, section 5.3.2.2) and thus cannot explain the less precise macroporosity prediction made by CB1 after harvesting. In contrast, the relationships between macroporosity and the landscape units and soil-landscape units were also weaker after harvesting (Chapter 5, section 5.3.4) and so do not explain the more precise predictions made by CB2 and CB4. The relationships between macroporosity and the terrain attributes were not a factor because they were effectively non-existent for macroporosity in the post-harvested plot (Chapter 5, section 5.3.4.3) and so the techniques that relied on those relationships (MLR and RK) could not be developed.

The poorer accuracy with which topsoil pH and available K were predicted in the post-harvested plot may be due to factors other than variance (i.e. predictive relationships) because there was essentially no difference between the two plots in terms of the variance of these properties. In the case of topsoil pH, the poorer accuracy of predictions given by CB4, MLR, and RK could be attributed to the weaker relationships between topsoil pH and the landscape units and terrain attributes after harvesting (Chapter 5, sections 5.3.4.1 and 5.3.4.3). However, the relationships between topsoil pH and the drainage classes (modified and broad) and soil-landscape units were either stronger or did not change after harvesting (Chapter 5, sections 5.3.2 and 5.3.4.2) and so do not explain the less precise predictions of topsoil pH given by CB1, CB2, and CB3 after harvesting. The decreased accuracy with which available K was predicted by CB1, CB3, CB4, MLR, and RK after harvesting may be due to the weaker post-harvesting relationships between the soil drainage classes (modified and broad), landscape units, and terrain attributes (Chapter 5, sections 5.3.2 and 5.3.4). The relationship between available K and the soil-landscape units remained unchanged after harvesting (Chapter 5, section 5.3.4.2) and so does not account for the poorer accuracy with which available K was predicted by CB2 in the post-harvested plot.

The technique giving the most precise predictions differed with the target property being predicted and the plot in which the predictions were made. OK performed particularly well, giving the most precise predictions of available Mg, P, and K in the pre-harvested plot and available Mg and P in the post-harvested plot. Also, OK was amongst the three most precise techniques for all target properties in the pre-harvested plot and half of the target properties in the post-harvested plot (topsoil pH, available Mg, and available P). RK gave the most precise predictions of available K in the post-harvested plot and total C in the pre-harvested whereas MLR gave the most precise predictions of total C and topsoil pH in the post-harvested plot. Macroporosity was most precisely predicted by CB1 in the pre-harvested plot and by CB4 in the post-harvested plot whereas the most precise prediction of topsoil pH in the pre-harvested plot was given by CB2. As expected, the REF technique was the least precise for most target properties in both plots. However, the CB3 technique gave the least precise predictions of total C in both plots and available K in the pre-harvested plot. The least precise prediction of macroporosity in the post-harvested plot was made by OK.

An assessment of prediction performance can be made by considering RMSE in association with ME but such an assessment will not be made here because a more robust assessment based on an analysis of ranks will be used instead. However, graphs plotting ME against RMSE for each target property in each plot are given in Appendix Four.

The measure of relative prediction accuracy, goodness-of-prediction (G) (Table 6.6) provides further insight into the differences between prediction techniques and between plots in terms of predictive accuracy. Also, G can provide some further indication of the absolute success of the prediction techniques (i.e. how close to the actual values the predictions came).

Table 6.6. Goodness-of-prediction (G) of prediction techniques in both plots (%).

Property†	Plot‡	Prediction technique§						
		CB1	**CB2**	**CB3**	**CB4**	**MLR**	**RK**	**OK**
Topsoil pH	Pre	21.70	37.62	19.65	31.08	27.29	30.53	33.75
	Post	17.33	17.48	21.98	18.40	33.20	33.20	23.64
Mg	Pre	15.84	43.22	15.23	42.98	30.01	49.68	57.64
	Post	8.99	10.11	13.28	1.65	-2.33	-	13.52
P	Pre	18.56	14.01	17.51	11.50	7.64	10.48	22.57
	Post	6.54	2.26	2.03	2.53	3.43	4.58	13.53
K	Pre	-3.79	12.38	-5.55	13.95	19.10	26.31	28.61
	Post	4.04	13.27	5.18	19.22	21.38	24.81	16.41
MP	Pre	23.36	5.49	20.47	2.57	1.32	4.28	12.64
	Post	5.38	3.24	0.87	10.67	-	-	-15.52
TC	Pre	5.68	6.73	-4.31	10.46	17.13	31.97	26.88
	Post	0.31	3.62	-3.10	10.39	16.96	11.95	9.34

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § CB1 = class-based technique 1, CB2 =class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging.

In general, the G values of all techniques in both plots were fairly low for most target properties. However, the G values achieved by some techniques in the prediction of available Mg in the pre-harvested plot were reasonably high (up to 50-60%). Also, some techniques achieved relatively high (>30%) G values in the prediction of topsoil pH in both plots and of total C in the pre-harvested plot. Although the performance of most techniques was far less than perfect, the range of G values given here is similar to those found in some studies of agricultural and range-land soils (Gotway *et al.*, 1996; Kravchenko and Bullock, 1999; Schloeder *et al.*, 2001). The relatively high G values achieved by some techniques in the prediction of some target properties (available Mg, topsoil pH, and total C in particular) indicate that those techniques gave substantially more precise predictions than the REF technique (the sample mean). In most other cases the prediction techniques did not give substantially more precise predictions. The more sophisticated prediction techniques (especially OK and RK but also MLR) tended to offer the greatest improvements in prediction accuracy for most target properties in both plots. However, one or both of the semi-quantitative soil-landscape modelling techniques (CB2 and CB4) offered similar or greater improvements in accuracy than those of the more sophisticated techniques for some target properties in the pre-harvested plot (topsoil pH and available Mg) and half the target properties in the post-harvested plot (available K, macroporosity, and total C). Furthermore, one or both of the other class-based techniques (CB1 and CB3) also offered similar or greater improvements in accuracy than those of the more sophisticated techniques for some target properties (topsoil pH and available Mg in the post-harvested plot, available P and macroporosity in the pre-harvested plot). These findings generally concur with the RMSE results.

The G values of most techniques were generally lower in the post-harvested than the pre-harvested plot indicating that, after forest harvesting, the prediction techniques were generally less precise relative to the accuracy of predictions made using the sample mean (REF technique). The implication of less relative improvement over the sample mean in the post-harvested plot is that most prediction techniques are generally less useful after harvesting for most target properties. The exceptions were available K, for which the majority of techniques gave higher G values in the post-harvested plot, and topsoil pH, where three of the seven techniques (CB3, MLR, and RK) gave higher G values in the post-harvested plot.

The causes of the differences in G values between the plots need to be considered with reference to the changes in the accuracy of the REF technique which, for most target properties in both plots, was the least precise technique. In the case of both topsoil pH and available K, the higher G values of some techniques in the post-harvested plot were due to the accuracy of the REF technique decreasing by more than it did for the other techniques. In other words, the accuracy of the REF was more adversely affected by forest harvesting than it was for the techniques with higher G values and that the latter were more resilient to the impacts of harvesting. The CB3 technique was one of the more resilient techniques for both topsoil pH and available K. The resilience of CB3 to the impacts of harvesting with respect to topsoil pH could be attributed to the stronger post-harvesting relationship between topsoil pH and the modified soil drainage classes. The relationships between topsoil pH and the terrain attributes were only slightly weakened after harvested, thus MLR and RK were also relatively resilient to with respect to topsoil pH.

Also, with respect to topsoil pH and available K, the lower G values that were found for some prediction techniques (CB1, CB2, CB4, and OK with topsoil pH; and OK and RK with available K) in the post-harvested plot were caused by the accuracy of the REF technique decreasing by less than that of these techniques. That is, the accuracy of other techniques was more adversely affected by harvesting than it was for the REF. The relationships between topsoil pH and the broad soil drainage classes, landscape units, and soil-landscape units either remained unchanged or became slightly weaker after harvesting and so do not adequately explain the relatively large reduction in the relative accuracy of CB1, CB2, and CB4. It is possible that an increase in the short-range variation of topsoil pH and available K after harvesting led to the fairly large reduction in the relative accuracy of OK for both properties. The relative accuracy with which RK predicted available K may have been made poorer by the weaker relationship between available K and the terrain attributes after harvesting.

Although prediction accuracy generally increased for both available Mg and available P in the post-harvested plot (Table 6.5), the G values decreased for these properties because the accuracy of the REF technique increased by more than that of the other techniques (probably because of the lower variance of these properties in the post-harvested plot). In the case of macroporosity, the accuracy of the REF technique increased while the accuracy of most of the other techniques (CB1, CB3, and OK) decreased, thus resulting in lower G values in the post-harvested plot. The accuracy of the CB2 and CB4 techniques increased after harvesting but only the accuracy of CB4 increased by a greater margin than that of the REF technique. Thus, the G value of CB2 decreased whereas the G value of CB4 increased after harvesting. The nominal increase in the variance of macroporosity after forest harvesting cannot explain the increase in the accuracy of the REF. However, the decrease in the relative accuracy with which the CB3 technique predicted macroporosity after harvesting may be attributed to the disruption (weakening) of the relationship between macroporosity and the modified soil drainage classes (Chapter 5, section 5.3.2.1). With respect to total C, the lower G values of some techniques (CB1, RK, and OK) in the post-harvested plot resulted from the accuracy of the REF technique decreasing by less than that of these techniques after harvesting. It appears that the REF technique was less affected by the significant increase in the variance of total C after harvesting than the other techniques were. Although the accuracy of the REF technique decreased by more than that of some other, initially more precise, techniques (CB2, CB4, and MLR) after harvesting, the G values of these techniques actually decreased slightly.

6.3.2.2 Relative performance

Individually, ME and RMSE provide useful measures of the bias and accuracy of prediction techniques, respectively. However, an analysis of the mean and standard deviation of prediction technique ranks provides a more robust measure of the relative prediction performance than the combined use of ME and RMSE can provide. Graphs plotting MR against SDR are given below (Figures 6.1-6.6) for each target property in each plot. MR is a measure of relative prediction accuracy. SDR is a measure of the consistency of a prediction technique in terms of its accuracy. The technique with the lowest MR is the most accurate and the technique with the lowest SDR is the most consistent. An assessment of prediction performance takes both measures into account and in this study both were considered with equal weight. A prediction technique with the lowest MR and the lowest SDR is the best predictor. However, the best predictor need not necessarily have the lowest MR or the lowest SDR provided the intersection of the two values is the closest to the origin (zero MR and zero SDR). In the following description of results the term ‘accuracy’ will be used when referring to the MR values and the term ‘consistency’ will be used when referring to the SDR values.

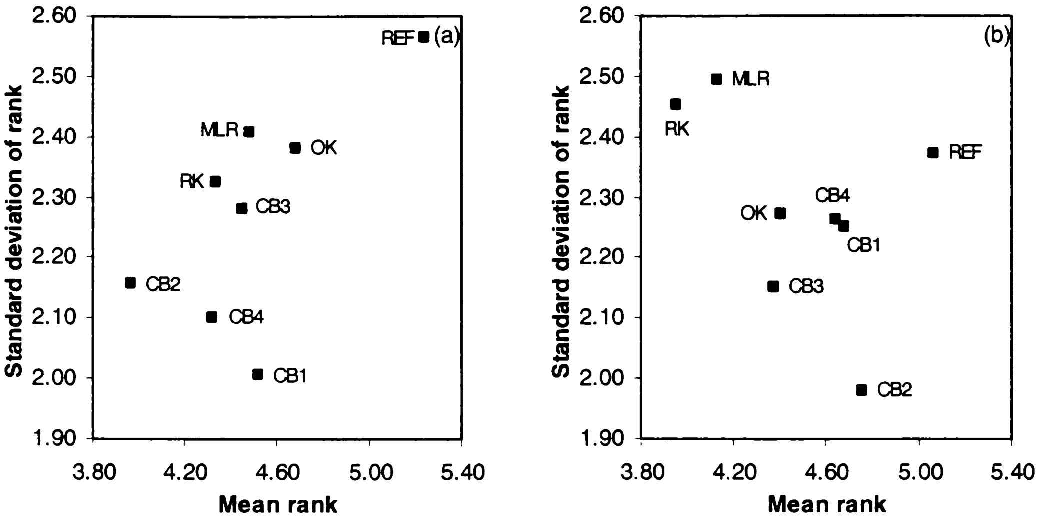

Figure 6.1. MR and SDR of techniques used to predict topsoil pH in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

The best performing method in the pre-harvested plot (Figure 6.1a) was CB2 which was the most accurate and third most consistent. CB1 was the most consistent technique but its overall performance was made poorer by its relatively low accuracy. CB4 was the second best performing technique, being the second most accurate and consistent. The RK technique also performed reasonably well, out performing both MLR and OK as expected (RK makes use of more information than MLR and OK). CB3 was the wost performing class-based technique. All prediction techniques performed substantially better than the REF which was the least accurate and least consistent.

In the post-harvested plot (Figure 6.1b), RK was the best predictor of topsoil pH but was only marginally better than CB3. Although RK was more accurate than CB3, it was considerably less consistent. MLR and OK were out-performed by RK as they were in the pre-harvested plot but the difference was slightly smaller. The REF was the worst performing technique but it was not the least consistent; RK and MLR were less consistent (but much more accurate). The main point of difference between the plots was that the three best performing techniques in the pre-harvested plot, CB2, CB4, and CB1, became the three worst performing techniques (excluding the REF) in the post-harvested plot. Also, the relative performances of CB3 and OK were better in the post-harvested plot.

Available Mg

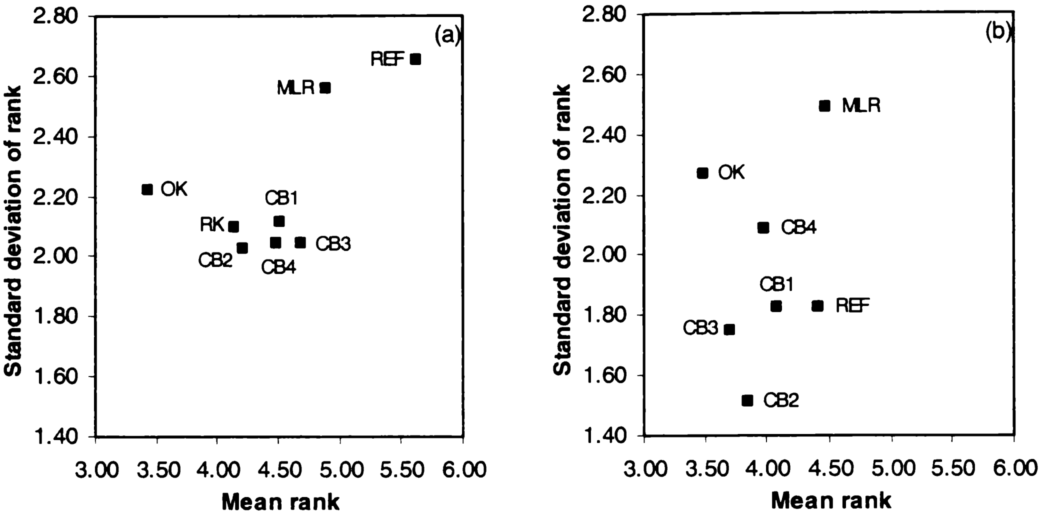

Figure 6.2. MR and SDR of techniques used to predict available Mg in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

In the prediction of available Mg, OK out-performed all other prediction techniques in the pre-harvested plot (Figure 6.2a). Most techniques were slightly more consistent than OK but all were less accurate. CB2 was the second-best performing technique, out-performing RK, MLR, and the other class-based techniques. MLR performed relatively badly and was only better than the REF which was the least accurate and least consistent. All other techniques, excluding MLR, performed substantially better than the REF. The second best performing class-based technique was CB4, which was slightly more accurate than CB1 and CB3.

In the post-harvested plot (Figure 6.2b), the CB2 technique was the best predictor of available Mg. However, CB2 performed only slightly better than CB3, which was marginally more accurate but less consistent. OK was the most accurate technique but was the second-most inconsistent. CB4 was the worst performing class-based technique. The worst performing technique overall was MLR and although the REF was only slightly more accurate, MLR was much less consistent. All techniques, apart from MLR, performed better than the REF. RK could not be used to predict available Mg in the post-harvested plot. As a consequence of having one less technique in the comparison, the MR values were slightly lower with a narrower range than in the pre-harvested plot. MLR is essentially useless for the prediction of available Mg in the post-harvested plot because a better result can be gained by using the sample mean.

Available P

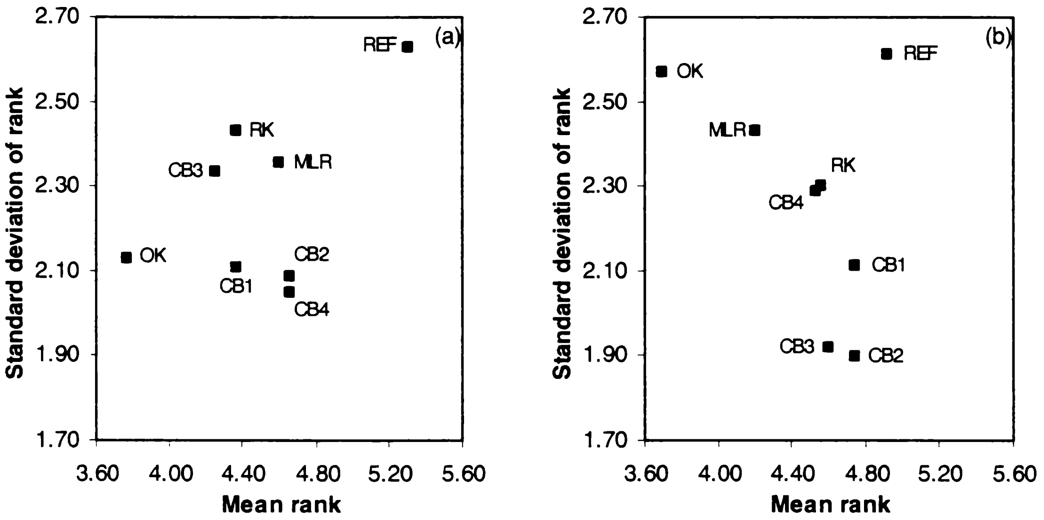

Figure 6.3. MR and SDR of techniques used to predict available P in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

The best predictor of available P in the pre-harvested plot (Figure 6.3a) was OK. Although OK was clearly the most accurate, some techniques were slightly more consistent (CB1, CB2, and CB4). CB1 was the best performing class-based technique followed by the more accurate but much less consistent CB3 technique. CB2 was the worst performing class-based technique. RK performed slightly better than MLR but worse than CB2. The REF was by far the worst predictor. Thus, all the other techniques offered a substantial improvement over the sample mean.

OK was also the best predictor of available P in the post-harvested plot (Figure 6.3b) despite being the second-most inconsistent technique (only the REF was less consistent). MLR was also fairly inconsistent but surprisingly out-performed RK (RK would normally be expected to out-perform MLR). CB3, the best performing class-based technique, was less accurate than MLR, CB4, and RK but considerably more consistent. Thus, CB3 was the second best performing technique. As in the pre-harvested plot, the REF was the worst performing technique.

Available K

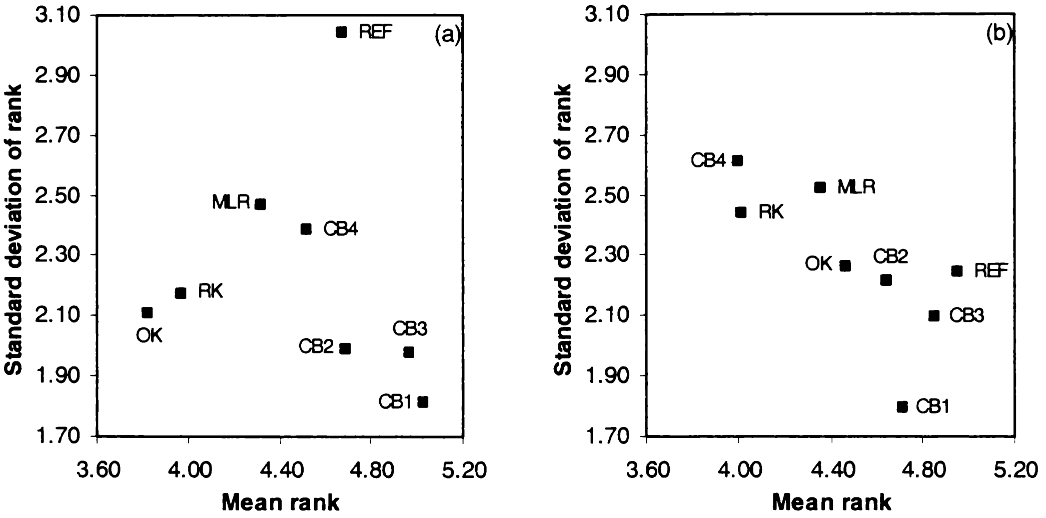

Figure 6.4. MR and SDR of techniques used to predict available K in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Figure 6.4a showed that available K was best predicted by OK in the pre-harvested plot. RK was the second best predictor because although it was less consistent than CB2, it was substantially more accurate. With the exception of CB4, the class-based techniques were unusually inaccurate (less accurate than the REF) yet still more consistent than the other techniques. CB2 was the best class-based predictor whereas the worst performing technique overall was the REF.

The best predictors of available K in the post-harvested plot (Figure 6.4b) were found to be RK closely followed by CB1. RK was the second most accurate technique (CB4 was slightly more accurate but less consistent) but was one of the least consistent whereas CB1 was one of the least accurate techniques but was clearly the most consistent. CB4 was the third best performing technique. The MLR, OK, CB2, and CB3 techniques all performed similarly, albeit for different reasons — for instance, MLR was more accurate but less consistent whereas CB3 was less accurate but more consistent. All prediction techniques performed only slightly better than the REF.

Macroporosity

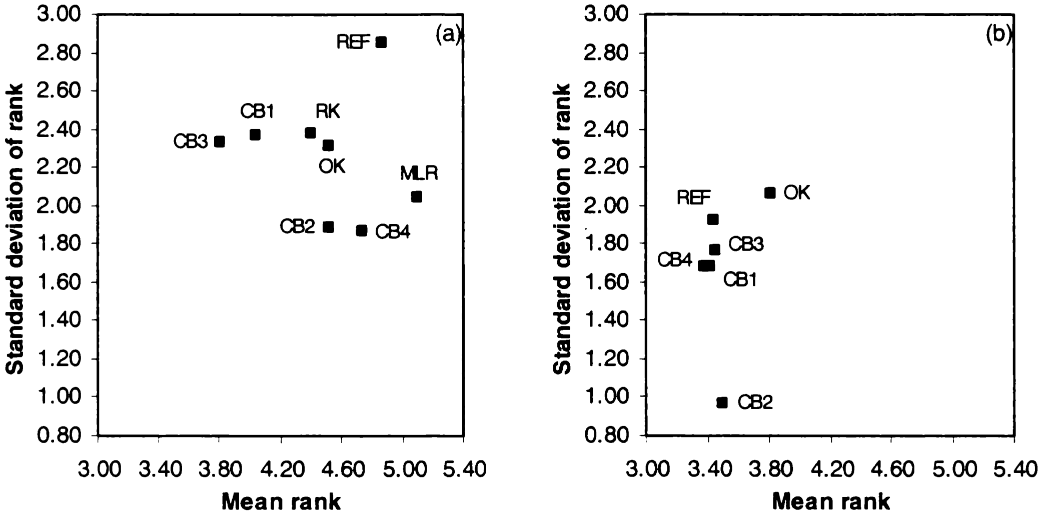

Figure 6.5. MR and SDR of techniques used to predict macroporosity in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Macroporosity was best predicted in the pre-harvested plot (Figure 6.5a) by CB3 with the other three class-based techniques (CB2, CB1, CB4) in second, third, and fourth positions, respectively. RK and OK performed similarly but MLR was somewhat less accurate (albeit slightly more consistent). MLR was less accurate than the REF but because the REF was considerably less consistent than MLR, the performance of the REF was worst overall. All techniques apart from the REF were similarly consistent.

Figure 6.5b showed that, for the prediction of macroporosity, the prediction techniques in the post-harvested plot had MR values that were lower with a narrower range than in the pre-harvested plot. These differences are the result of there being two fewer prediction techniques in the comparison: MLR and RK, which could not be used to predict macroporosity in the post-harvested plot because the relationships between macroporosity and the terrain attributes were not sufficiently strong. All prediction techniques were similarly accurate with the exception of OK which was less accurate than the others. Therefore, differences in consistency largely dictated the differences in the relative performance of the techniques. As in the pre-harvested plot, the class-based techniques were the best predictors. However, in the post-harvested plot, CB2 was the best predictor followed by CB4, CB1, and CB3 in second, third, and fourth positions, respectively. The CB2 technique was clearly more consistent than all other techniques which were similarly consistent. The REF technique performed worse than the class-based techniques but better than OK which was the worst performing technique. Thus, OK was effectively of no value in the prediction of macroporosity in the post-harvested plot. The MLR and RK techniques could also be considered to have failed similarly because they could not even be applied.

Total C

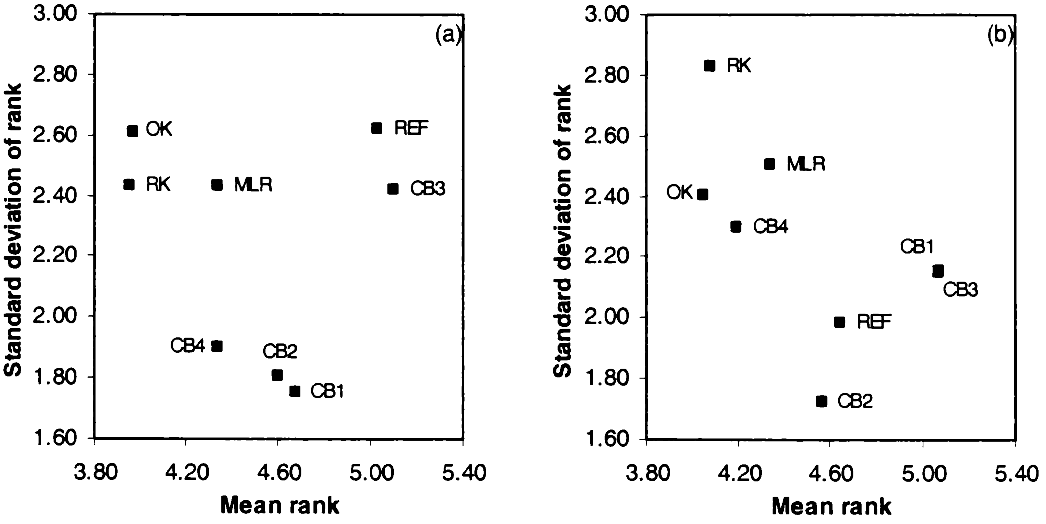

Figure 6.6. MR and SDR of techniques used to predict total C in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

The best predictor of total C in the pre-harvested plot (Figure 6.6a) was CB4 closely followed by RK. RK was more accurate than CB4 but much less consistent. The CB1 and CB2 techniques were more consistent than CB4 but less accurate. Also, CB1 and CB2 performed better than OK because they were much more consistent (which compensated for their lack of accuracy). Conversely, the performance of OK and MLR, which were more accurate than CB1 and CB2, was hampered by a lack of consistency. The performance of CB3 was poor: it was less accurate than the REF but performed slightly better than the REF overall due to its greater consistency.

In the post-harvested plot, CB2 was the best predictor of total C (Figure 6.6b). Several techniques (OK, RK, CB4, and MLR) were more accurate but were much less consistent. In contrast to the results for the pre-harvested plot, OK out-performed RK due to an improvement in the consistency of OK (and a reduction in the consistency of RK), and was the second best predictor of total C. CB4 was the third best predictor, being less accurate than OK but more consistent. Unusually, the REF technique performed particularly well, giving better predictions than RK, MLR, CB3, and CB1. Also, in contrast to findings for the pre-harvested plot, CB1 was the poorest performing predictor. The RK, MLR, CB3, and CB1 techniques are effectively useless for predicting total C in the post-harvested plot because they performed less well than the sample mean which might as well be used in their stead.

Overview of relative performance

All prediction techniques were reasonably similar with respect to accuracy (MR values were similar) for all target properties in both plots (Figures 6.1-6.6). Comparable findings were indicated also by the RMSE values (Table 6.5). The MR values of most prediction techniques ranged between 3.50 and 5.50 for most target properties. The range in MR values was fairly central on the spectrum of ranks (between 1 and 8) suggesting that there may be considerable variation in the accuracy of all prediction techniques from one validation point to another. However, the SDR values are comparatively low in relation to some values reported in other similar studies (Laslett *et al.*, 1987; Odeh *et al.*, 1995; Triantifilis *et al.*, 2001). The range in SDR values was fairly narrow also (roughly between 1.50 and 3.00) for most target properties in both plots. Therefore, it could be inferred that the performance of all prediction techniques (even including the REF) was fairly similar.

The best performing prediction technique tended to differ with target property and plot. That is, no one technique performed best for all target properties in either plot. In the pre-harvested plot, three of the six target properties (available Mg, P, and K) were best predicted by OK. The remaining three target properties (topsoil pH, macroporosity, and total C) were best predicted by class-based techniques (CB2, CB3, and CB4, respectively). In the post-harvested plot, half of the target properties (available Mg, macroporosity, and total C) were best predicted by the CB2 technique. Two of the remaining target properties (topsoil pH and available K) were best predicted by RK and the other (available P) by OK.

The relative performance of the prediction techniques was also assessed for all target properties in combination in order to determine which techniques perform the best in general and to help clarify the impacts of forest harvesting on prediction performance. Within each plot, MR and SDR (Figure 6.7) were calculated for each prediction technique based on the squared prediction errors of all target properties at the validation points in each plot.

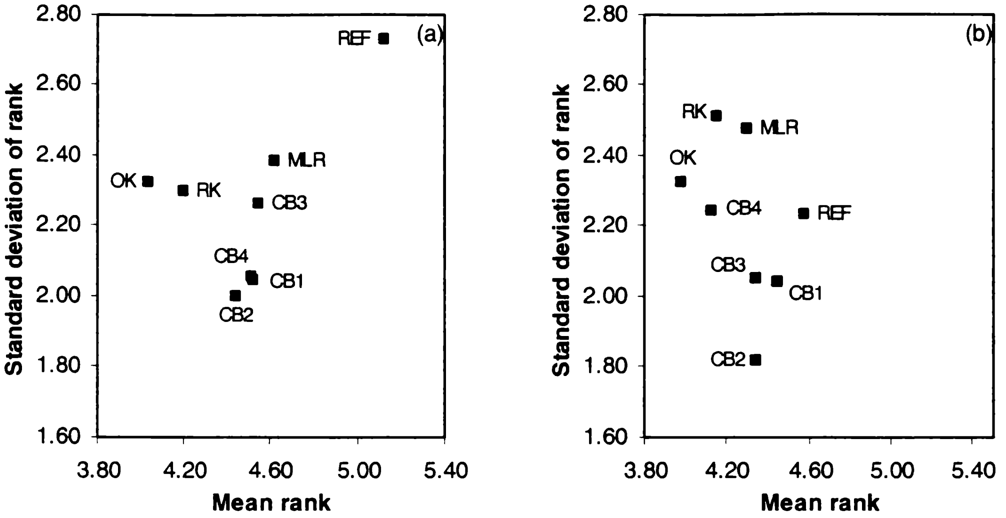

Figure 6.7. MR and SDR of techniques used to predict all target properties in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Over all target properties, the best predictor in the pre-harvested plot (Figure 6.7a) was OK, which was the most accurate technique. RK, which performed relatively well, was slightly less accurate than OK but was a little more consistent. The second best performing technique, just ahead of RK, was CB2. All of the class-based techniques were less accurate than OK and RK but were more consistent. CB2, CB1, and CB4 performed similarly but CB2 was slightly more accurate and consistent than CB1 and CB4. CB3 was the worst performing class-based technique. MLR was less accurate and less consistent than all other techniques with the exception of the REF which was the least accurate and least consistent.

In the post-harvested plot, (Figure 6.7b) CB2 was the best performing technique over all target properties. Although several techniques (OK, RK, MLR, and CB4) were more accurate, they were much less consistent than CB2 and thus performed less well on balance. OK was the second best performing technique ahead of CB4, CB3, and CB1 in that order. RK performed relatively poorly being only slightly more accurate than MLR but less consistent. The REF was the worst performing technique and although it was the least accurate, several techniques were less consistent (OK, RK, MLR, and CB4). The separation between the REF and the other techniques was clearly less pronounced in the post-harvested plot than in the pre-harvested.

Figure 6.7 shows that, within each plot, the prediction techniques essentially fell into one of two fairly distinct groupings. In the pre-harvested plot, most of the class-based techniques (CB1, CB2, and CB4) form one group whereas the geostatistical and quantitative soil-landscape modelling techniques (OK, RK, and MLR), in addition to one class-based technique (CB3), form the other. A similar grouping occurs in the post-harvested plot except that the CB3 technique replaces the CB4 technique in the group dominated by the class-based techniques and vice-versa with respect to the group dominated by the geostatistical and quantitative soil-landscape modelling techniques. These groupings, revealed by the examination of performance over all target properties, reflect the general patterns that occurred for most of the target properties individually but were sometimes not as clearly shown by the graphs (Figures 6.1b-6.6b). Over all target properties in both plots, the majority of class-based techniques were generally less accurate than the geostatistical and quantitative soil-landscape modelling techniques but were often substantially more consistent. Thus, there was a tendency for two separate clusters of points to form. This separation of techniques is consistent with the RMSE data (Table 6.5) which indicated that the more sophisticated geostatistical and quantitative soil-landscape modelling techniques were generally a little more precise than most of the class-based techniques. The likely reasons for the greater accuracy of the OK, RK, and MLR techniques were given in the discussion of the RMSE results.

The relative performance of RK was substantially poorer in the post-harvested plot than in the pre-harvested over all target properties. The alteration of the target property values by forest harvesting led to a weakening of the relationships between all target properties (except for total C) and the terrain attributes (Chapter 5, section 5.3.4.3). The poorer performance of RK over all target properties after harvesting could be attributed to these weaker quantitative soil-landscape relationships. However, for those target properties in which the relative performance of RK actually improved after harvesting (topsoil pH and available

K), RK became the best performing technique. Over all target properties, the relative performance of OK was also poorer in the post-harvested plot than in the pre-harvested, but only slightly. However, the relative performance of OK was improved for some target properties (topsoil pH and total C) after harvesting. Nevertheless, OK was relatively resistant to the affects of forest harvesting because it does not rely on the predictive relationships which were generally weakened by forest harvesting disturbance.

Over all target properties, there was essentially no change in the relative performance of MLR, CB1, and the REF after harvesting. MLR was generally one of the poorer performing techniques in both plots although its relative performance was improved for some target properties (topsoil pH, available P, and total C) after harvesting. Even though forest harvesting weakened the relationships between most target properties and the terrain attributes (Chapter 5, section 5.3.4.3), the relationships were relatively weak in the pre-harvested plot in the first instance for all target properties except perhaps available Mg. Therefore, the weakening of these quantitative soil-landscape relationships by forest harvesting did not result in a substantial change in the relative performance of MLR. The CB1 technique generally performed better than MLR over all target properties in both plots, but was also one of the poorer performing techniques. Also, the relative performance of CB1 was poorer for half of the target properties (topsoil pH, available P, and total C) after harvesting. The relationships between most target properties and the broad soil drainage classes were not made weaker by forest harvesting (Chapter 5, section 5.3.2.2). Therefore, forest harvesting had a fairly neutral impact on the performance of CB1 overall. The relative performance of the REF technique was similarly poor in both plots over all target properties. However, the relative performance of the REF was improved after harvesting for some target properties (available Mg, macroporosity, and total C). The post-harvesting improvement in the relative performance of REF with respect to these properties may simply be due to the relatively poorer performance of some other techniques (e.g. RK and MLR). Nevertheless, the gap in performance between the REF and most other techniques was reasonably wide for most target properties in the pre-harvested plot but was generally not as wide in the post-harvested (as was indicated by the reduction in G values after harvesting; see Table 6.6). That is, most prediction techniques offered less of an improvement in performance over the REF after forest harvesting which means that these techniques were of comparatively less value for target property prediction after harvesting.

The CB2, CB3, and CB4 techniques performed relatively better in the post-harvested plot than in the pre-harvested over all target properties. The relative performance of CB2 was improved for most target properties after harvesting, with topsoil pH and available K being the only properties for which the relative performance was poorer. The relative performance of CB3 was improved or remained the same for most target properties (decreased only for macroporosity) after harvesting whereas the relative performance of CB4 was improved for half of the target properties (available K, macroporosity, and total C) after harvesting. The relationships between all target properties (except macroporosity) and the soil-landscape units were not adversely affected by forest harvesting (Chapter 5, section 5.3.4.2) because the relationships between most target properties and the broad soil drainage classes were not weakened by harvesting (Chapter 5, section 5.3.2.2) and also because the relationships between the broad drainage classes and the landscape units in the post-harvested plot were almost as strong as those in the pre-harvested plot (Chapter 4, section 4.3.3.1). Thus, the CB2 technique is relatively resilient to the impacts of forest harvesting and, as a consequence, it performed relatively better than the more sophisticated techniques (OK, RK, and MLR) after harvesting. The relationships between all target properties (except topsoil pH) and the modified soil drainage classes were weakened by forest harvesting (Chapter 5, section 5.3.2.1) as were the relationships between all target properties (except total C) and the landscape units (Chapter 5, section 5.3.4.1). These weakened relationships do not explain the improved performance of the CB3 and CB4 techniques after harvesting. Perhaps CB3 and CB4 were relatively resistant to the effects of forest harvesting because they make use of fairly detailed soil class or landscape unit information.

The OK technique is the best predictor over all target properties in the pre-harvested plot and the second best in the post-harvested plot. Therefore, it could thus be argued that OK is an effective predictor of target properties in a plantation forest environment because not only does it perform well under mature trees but it also performs relatively well after forest harvesting. However, in this study, all target property predictions were made using data collected from a reasonably dense sampling grid. Such a dense sampling design would be impractical for producing target property maps for areas the size of an entire plantation forest. It is possible that, for some target properties, the sampling density required to achieve a similar level of performance from OK at the spatial extent of an entire forest would require excessively large numbers of samples to be taken and analysed thus making the OK technique uneconomic for the purpose of mapping target properties across whole forest estates (McKenzie and Austin, 1993; Kravchenko, 2003).

The second best performing technique over all target properties in the pre-harvested plot, CB2, became the best performing technique after harvesting because it tended to be less adversely affected by the impacts of forest harvesting than the other techniques. Therefore, CB2 is a very useful technique because it can be successfully applied to map target properties in both pre- and post-harvested areas. Although CB2 was out-performed by OK in the pre-harvested plot, its performance in that plot was still relatively good. Moreover, it has the potential to be more practical and cost effective. A well-constructed and accurate soil-landscape unit map would allow for the CB2 method to be readily applied across an entire forest (Webb and Burgham, 1997). Rather than taking samples according to a grid design, a suitable number of samples could be taken from an appropriate number of replicate soil-landscape unit delineations, randomly selected across the area being mapped, in order to calculate the mean target property values for each soil-landscape unit. With the CB2 technique, the potential exists for an adequate level of predictive performance to be maintained with a reduced number of soil samples provided the relationships between the landscape units, locally significant soil classes, and target properties recur throughout the landscape and that the target property variability within soil-landscape units is not too great. Therefore, the performance of the CB2 technique is very much dependent on the development of accurate qualitative soil-landscape models.

The RK technique was the third best performing technique over all target properties in the pre-harvested plot but performed much less well after harvesting. This technique, while reasonably effective in pre-harvested areas, may not be so in post-harvested areas because the quantitative soil-landscape relationships were weakened by harvesting disturbance for all target properties (except total C). The CB4 technique was the fourth best performing technique over all target properties in the pre-harvested plot but became the third best performing technique after harvesting. Therefore, this technique could provide a cost-effective alternative to the OK technique for mapping target properties in post-harvested areas. Also, the CB4 technique could possibly be applied more cheaply than the CB2 technique because it does not necessarily require the identification of soil classes and the development of qualitative soil-landscape relationships to make target property predictions — the predictions are made in a similar fashion to those of CB2 but from landscape units alone. However, the value of landscape units defined without reference to locally significant soil classes is probably questionable. Moreover, the results of this study show that the CB2 technique can provide generally better predictions over all target properties in both plots than the CB4 technique for which the landscape units were defined in relation to soil classes.

In addition to not performing very well, the CB1 and CB3 techniques may not be particularly practical for use in mapping the target properties across entire plantation forests. To attain the modest predictive success achieved by CB1 and CB3 in this study across a whole forest, very accurate soil class maps would be required to provide accurate soil class information at unvisited locations so that the predictions could be made. The CB3 technique would require an even more detailed soil class map than the CB1 technique. The cost of producing sufficiently accurate and detailed soil class maps over an entire forest for the application of the CB1 and CB3 techniques is likely to be prohibitive.

6.4 Summary and conclusions

All prediction techniques gave fairly unbiased predictions ($-1 < ME < 1$). Moreover, all techniques gave similarly unbiased predictions of most target soil properties in either pre- or post-harvested plots. The accuracy of all techniques (including the reference) was also reasonably similar for most target soil properties in either plot. However, the geostatistical and quantitative soil-landscape modelling techniques (ordinary kriging, regression kriging, and multi-linear regression) and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques (class-based 2 and 4) tended to be slightly more precise than the other class-based and reference techniques. A corollary of the similarity in accuracy was that, in general, most techniques were not substantially more precise than the sample mean (reference). However, in some instances, the geostatistical and quantitative soil-landscape modelling techniques and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques did offer substantial improvements in accuracy over that of the sample mean. In concurrence with the bias and accuracy results, the assessment of relative performance indicated that the accuracy and consistency of all techniques was fairly similar — the range in mean rank and standard deviation of rank values for all target soil properties in either plot was reasonably narrow. Therefore, it is concluded that, within a given plot, the performance of all prediction techniques (including the reference) was generally similar for all target soil properties. However, the geostatistical and quantitative soil-landscape modelling techniques, and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques tended to be slightly more accurate than the less sophisticated techniques and as such tended offer a greater improvement over the sample mean. On the other hand, the majority of class-based techniques tended to be more consistent than the more sophisticated techniques.

A comparison of the pre- and post-harvested plots revealed that most techniques gave less biased predictions of most target soil properties after forest harvesting and that prior to harvesting most predictions were under-estimates whereas after harvesting most predictions were over-estimates. Furthermore, it was found that the predictions of most techniques were slightly less precise after harvesting for most target soil properties. In some cases, the reduction in accuracy of predictions could be attributed to the weakening of some relationships between the target soil properties and the soil drainage classes (modified and broad), landscape units, and terrain attributes caused by forest harvesting (Chapter 5). However, in most cases the reduction (or increase) in accuracy could not be explained by the harvesting-related changes to the predictive relationships. For total C, the reduction in accuracy was probably due largely to the increase in the variance of that property caused by forest harvesting. The prediction accuracy of most techniques increased after harvesting for available Mg and P. For these properties, the increase in accuracy was attributed to a decrease in variance which may have been caused by the change in vegetation cover that necessarily resulted from forest harvesting.

Most prediction techniques offered less of an improvement in accuracy over the sample mean after harvesting for most target soil properties. Therefore, most techniques became relatively less useful after harvesting. The reduction in the goodness-of-prediction values after harvesting occurred because the accuracy of the reference technique either was decreased by less than that of the other techniques or it was increased by more than that of the other techniques. In some cases (e.g. available K) the goodness-of-prediction values of some techniques increased after harvesting. This increase was caused by the accuracy of the reference technique being decreased by more than that of the other techniques. The weakening of some predictive relationships by forest harvesting explained the reduction in relative performance in some cases but not others.

In terms of the comparison of relative performance between the plots, it was found that no one prediction technique performed best for all target soil properties in either plot. However, half of the target soil properties in the pre-harvested plot were best predicted by ordinary kriging whereas half of the target soil properties in the post-harvested plot were best predicted by the class-based 2 technique. Furthermore, some general effects of forest harvesting were identified over all target soil properties. After forest harvesting, the relative performance of some prediction techniques (regression kriging and ordinary kriging) generally became poorer whereas the relative performance of other techniques (class-based 2, class-based 3, and class-based 4) generally improved. On balance, the relative performances of the class-based 1, multi-linear regression, and reference techniques remained the same. The prediction techniques that showed an improvement in relative performance after harvesting (e.g. the semi-quantitative soil-landscape models) were generally more resilient to the disturbance caused by forest harvesting than were the other techniques due to the nature of the relationships on which their predictions were based. Even the weakening of some of these predictive relationships by forest harvesting did not impair the relative performance of some techniques (class-based 3 and 4).

In conclusion, the geostatistical technique (ordinary kriging) is the best predictor of target soil properties in the pre-harvested areas of southern Mahurangi Forest whereas a semi-quantitative soil-landscape modelling technique (class-based 2) is the best within the post-harvested areas. Furthermore, the class-based 2 technique has the potential to offer a more practical and cost-effective alternative to ordinary kriging throughout the forest. However, the performance of the class-based 2 technique is very much dependent on the development of accurate qualitative soil-landscape models. The other techniques (including the quantitative soil-landscape models) either failed to perform well after harvesting or were likely to be less cost-effective, or both.

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CHAPTER SEVEN

Synthesis and conclusions

7.1 Introduction

Soil-landscape modelling approaches to the spatial prediction of soil classes or target soil properties have generally been found to perform well in agricultural or range-land environments (e.g. Rijkse and Trangmar, 1995; Bishop and McBratney, 2001) and have the advantages of being relatively cost effective (Hewitt, 1993) and able to provide a range of soil information in different formats (Thwaites and Slater, 2000). Therefore, soil-landscape modelling has been identified as a potentially useful tool for collecting the soil class and target property information required by forest managers for the sustainable and site-specific management of their estates (Thwaites and Slater, 2000).

Forest land-management activities such as clear-fell harvesting can cause considerable soil disturbance (Simard *et al.*, 2001; Palmer *et al.*, 2004) and have been shown to significantly alter the magnitude of soil properties in both New Zealand (e.g. Parfitt *et al.*, 2002) and elsewhere (e.g. Simard *et al.*, 2001). Thus, the soil-landscape relationships used by soil-landscape models to predict soil spatial distribution patterns may be altered or weakened by forest harvesting (Block *et al.*, 2002) which, in turn, may reduce the predictive performance of soil-landscape models. Prior to this study, the impacts of forest harvesting on soil-landscape relationships and the predictive performance of soil-landscape modelling had not been investigated. In this study, hauler-based, clear-fell, forest harvesting was shown to have impaired the relative performance of some quantitative soil-landscape modelling and geostatistical techniques for the spatial prediction of target soil properties. However, the relative performance of the other soil property prediction techniques and the performance of the qualitative soil-landscape modelling approach were not adversely affected. Forest harvesting was also found to have altered and weakened some of the relationships between the target soil properties and the landscape and soil drainage classes.

7.2 Overview and synthesis of results

7.2.1 Spatial prediction of soil drainage classes: impacts of forest harvesting on qualitative soil-landscape modelling

Two qualitative soil-landscape models for the spatial prediction of soil drainage classes were developed within southern Mahurangi Forest – one in a pre-harvested area, the other in a post-harvested area – in order to determine the impacts of forest harvesting on the predictive performance of qualitative soil-landscape modelling. It was necessary to identify and define the locally significant soil classes, landscape units, and soil-landscape units for the purposes of developing the class-based techniques for the spatial prediction of target soil properties.

7.2.1.1 Identification of locally significant soil classes

The soils of southern Mahurangi Forest differ predominantly in terms of soil drainage condition. Therefore, the soil continuum within the forest was found to be most effectively partitioned using soil drainage classes. Although the groups and subgroups of the NZSC (Hewitt, 1998) communicated differences in the drainage, parent materials, potential nutrient status, profile evolution, and general landscape position of the soils within the forest, they would have introduced an unnecessary level of detail and complexity to the qualitative soil-landscape models. However, the NZSC subgroups were used to help define the soil drainage classes and to better understand the detailed soil-landscape relationships.

A modified version of the New Zealand soil drainage classification (Milne *et al.*, 1995) was developed to partition better the local variation in soil profile hydromorphology. Four modified drainage classes were defined: (1) Well Drained, (2) Imperfectly Drained, (3) Somewhat Poorly Drained, and (4) Poorly Drained. The key modification was the subdivision of the existing imperfectly drained class into two new classes (Imperfectly Drained and Somewhat Poorly Drained) on the basis of the presence or absence of redox depletions within the upper part of the profile. Redox-mottled horizons that contain redox depletions are likely to be reduced for longer periods than those without (Vepraskas, 1994;

Birkeland, 1999). Therefore, the presence of redox depletions is probably an indicator of more impeded drainage. The subdivision of the imperfectly drained soils was subsequently found to be important with respect to differences in the target soil properties (section 7.2.2.3). The modified soil drainage classes were identified as the locally significant soil classes and these were used as the primary classes of the qualitative soil-landscape models. The modified drainage classes were amalgamated into two broad drainage classes (Wet soils and Dry soils) to improve the practicality of the models. The Well and Imperfectly Drained soils were combined to form the Dry class whereas the Wet class encompassed the Somewhat Poorly and Poorly Drained soils. The broad and modified drainage classes formed the basis of the class-based 1 and class-based 3 techniques, respectively, used in the spatial prediction of the target soil properties (section 7.2.3).

The Dry soils were found to be naturally more abundant within the post-harvested plot than within the pre-harvested (Table 7.1).

Table 7.1. Abundances of the broad and modified soil drainage classes in both plots.

Drainage classes		Abundance (%)	
		Pre-harvested plot	**Post-harvested plot**
Broad classes	Dry soils	53	67
	Wet soils	47	33
Modified classes	Well Drained	30	18
	Imperfectly Drained	23	49
	Somewhat Poorly Drained	29	24
	Poorly Drained	18	9

Approximately half of the soils in the pre-harvested plot are of the Dry class whereas almost 70% of the soils in the post-harvested plot were classified as Dry. More specifically, the Imperfectly Drained soils are more than twice as common and the Well and Poorly Drained soils are about half as common in the post-harvested plot as they are in the pre-harvested plot. The greater abundance of Imperfectly Drained soils accounts for the greater abundance of Dry soils in the post-harvested plot. Forest harvesting may, to a limited extent, be partly responsible for the lower abundance of Well Drained soils and the greater abundance of Imperfectly Drained soils in the post-harvested plot. The soil compaction cause by harvesting machinery (section 7.2.2.1) may have impeded the drainage of some antecedent Well Drained soils which could have resulted in the formation of redox segregations in the upper part of the profile and the subsequent classification of those profiles as Imperfectly Drained soils.

7.2.1.2 Identification of functional landscape units

Soil drainage within the forest is controlled largely by geomorphic factors. Therefore, landscape frameworks were developed to emphasise geomorphic factors relevant to water movement in order to better predict soil drainage. In each plot the refined landscape framework consisted of a broad, three-tiered hierarchical subdivision of the landscape with the land system at the broadest level of the hierarchy. At the second level, the land system was subdivided into three land zones: (1) Upper, (2) Middle, and (3) Lower. The Middle zone in each plot was further subdivided into two land sub-zones which represent the third level of the hierarchy. The land zones comprise an amalgam of land elements and sub-elements which usually occur adjacent to one another in a similar part (zone) of the landscape. Land sub-zones represent the subdivision of a zone according to a specific geomorphic factor/terrain attribute (e.g. slope-shape or relative elevation), and have the purpose of attaining more clearly defined soil-landscape relationships. The two refined landscape frameworks differ at the sub-zone level of the hierarchy because a different geomorphic factor/terrain attribute was used to define the sub-zones of each framework.

The landscape units of the models were defined to be the final versions of the zones and sub-zones of each framework (Figure 7.1). The four landscape units of the pre-harvested framework were (1) Upper, (2) Middle-High, (3) Middle-Low, and (4) Lower, whereas the four landscape units of the post-harvested framework were defined as (1) Upper, (2) Middle-Divergent, (3) Middle-Convergent, and (4) Lower. The landscape units of each model formed the basis of the class-based 4 technique used in the spatial prediction of the target soil properties (section 7.2.3).

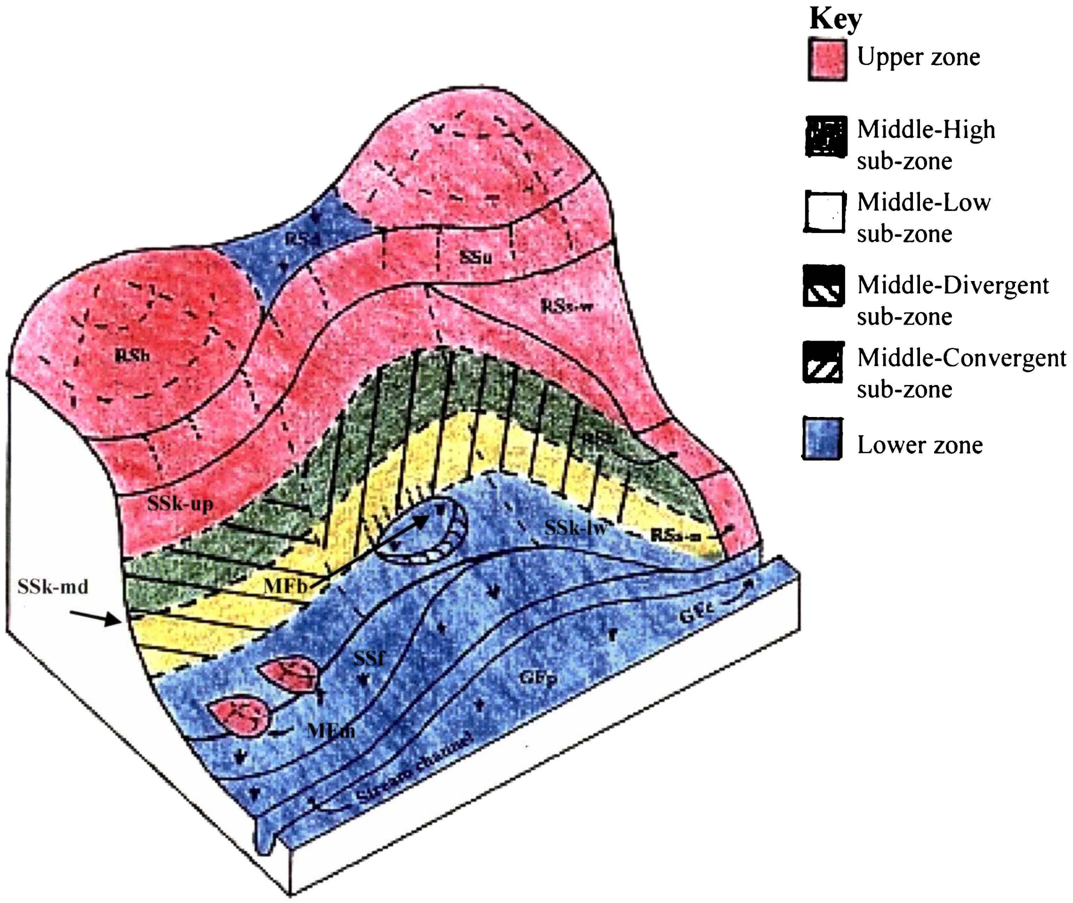
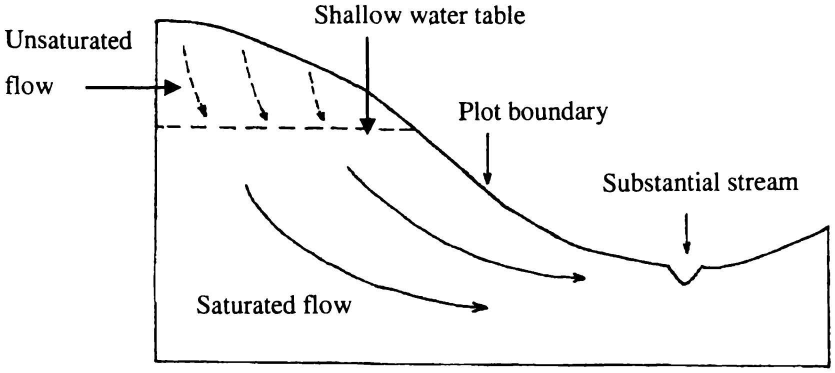


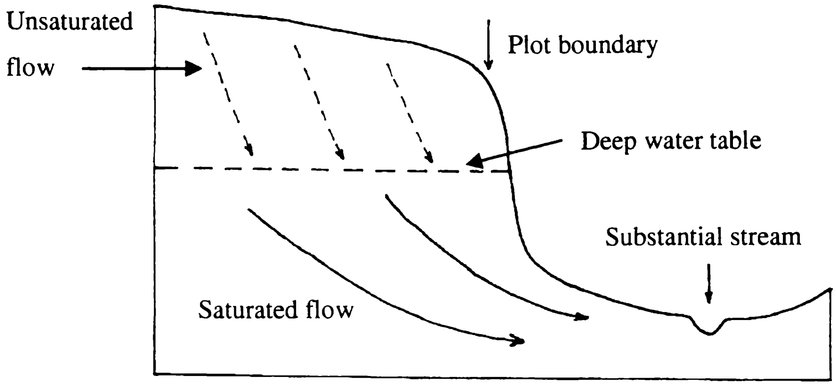
Figure 7.1. An idealised block diagram illustrating the nature and position of the land zones and sub-zones within both plots. Key: RSs-n = narrow ridge summit slopes, RSs-w = wide ridge summit slopes, RSb = ridge summit bench, RSh = ridge summit hillock, RSd = ridge summit saddle, SSu = side-slope shoulder, SSk-up = upper side-slope back-slope, SSk-md = middle side-slope back-slope, SSk-lw = lower side-slope back-slope, SSf = side-slope foot-slope, GFp = gully floor floodplain, GFc = gully floor channel, MFm = mudslide feature mound, MFb = mudslide feature bench.

7.2.1.3 Differences in the landscape hydrology of the plots

A naturally occurring difference in the landscape structures of the pre- and post-harvested plots appears to have resulted in the plots having somewhat different landscape hydrologies. The hanging nature of the post-harvested sub-catchment has probably resulted in strong hydraulic gradients and a relatively deep water table across the plot (Figure 7.2). Consequently, the landscape units in the post-harvested plot are, in general, likely to drain faster than those in the pre-harvested plot where the hydraulic gradients are probably weaker and the water table shallower. The difference in landscape hydrology may explain the greater abundance of Dry soils in the post-harvested plot than in the pre-harvested.



Pre-harvested sub-catchment



Post-harvested sub-catchment

Figure 7.2. Landscape structure and hydrology of the pre- and post-harvested plots (sub-catchments).

7.2.1.4 Impacts of forest harvesting on the relationships between the soil drainage classes and the landscape units (Objective 1a)

In the pre-harvested plot, the Upper and Middle-High landscape units were dominated by the Dry soils whereas the Middle-Low and Lower units were dominated by Wet soils (Figure 7.3).

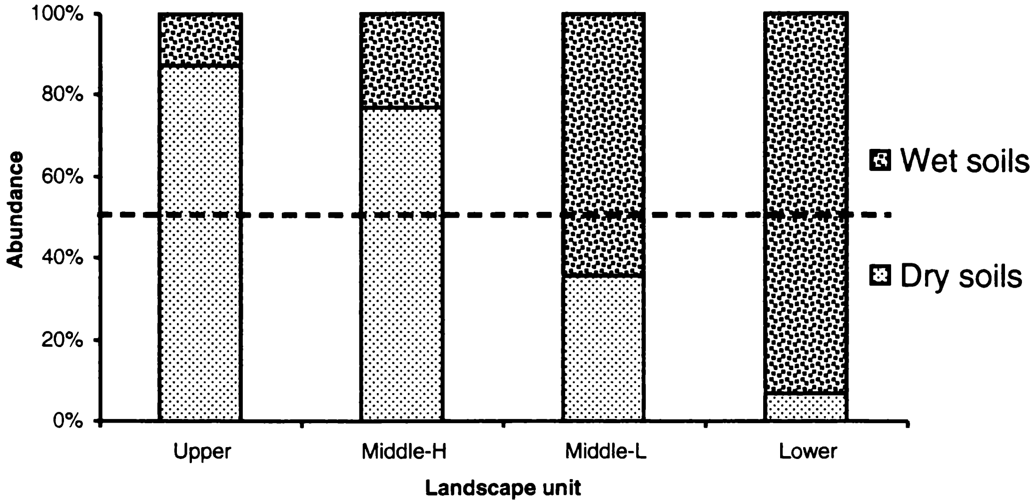


Figure 7.3. Abundance of broad soil drainage classes in the landscape units of the pre-harvested model. The dashed line indicates an abundance of 50% which represents the threshold used in the definition of the soil-landscape units (the class with an abundance > 50% is considered dominant).

The relationships between the landscape units and the broad drainage classes of the post-harvested model (Figure 7.4) are similar to those of the pre-harvested model but with several key exceptions. Firstly, the Dry soils dominate the Middle-Convergent unit whereas the equivalent unit in the pre-harvested plot (Middle-Low) was dominated by the Wet soils. Secondly, the Dry soils are more common in the Lower unit than is the case for the Lower unit of the pre-harvested model.

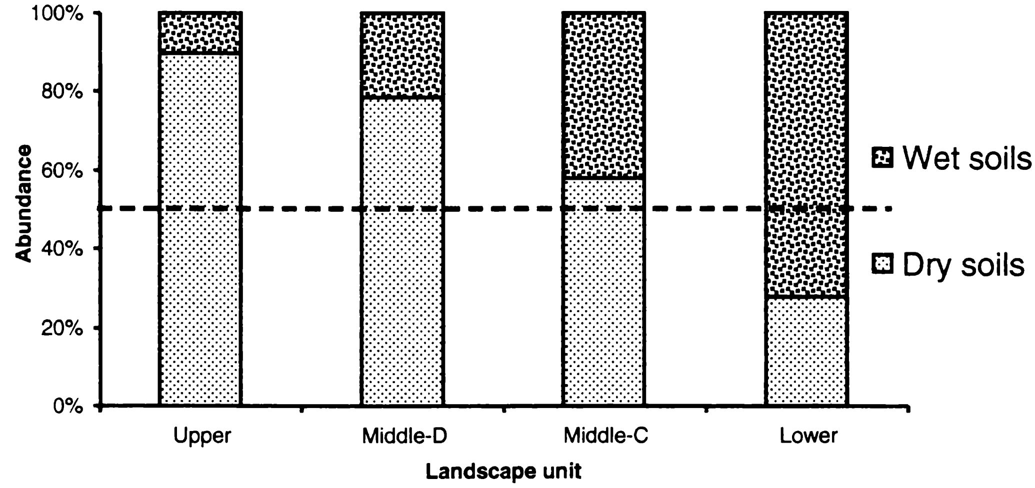


Figure 7.4. Abundance of broad soil drainage classes in the landscape units of the post-harvested model. The dashed line indicates an abundance of 50% which represents the threshold used in the definition of the soil-landscape units (the class with an abundance > 50% is considered dominant).

The relationships between the broad drainage classes and the landscape units are fractionally weaker in the post-harvest plot than in the pre-harvested. However, the weaker relationships are probably attributable to the generally drier nature of the landscape in the post-harvested plot and are not likely to be due to forest harvesting. The reduction in the abundance of the Well Drained soils in the Upper unit after harvesting (Chapter 4, Figures 4.16 and 4.17) could be attributed to soil compaction and the formation of redox segregations caused by forest harvesting activities. However, this effect is only minor because the overall abundance of the Dry soils was not reduced after harvesting (i.e. the reduction in the abundance of the Well Drained soils was offset by an increase in the abundance of the Imperfectly Drained soils).

7.2.1.5 Identification of functional soil-landscape units

The soil-landscape relationships comprising the two models are encapsulated and expressed in the form of soil-landscape units. That is, the soil-landscape units represent the integration of the landscape units and the broad soil drainage classes for the purpose of predicting those drainage classes across the landscape. The soil-landscape units were defined on the basis of the dominant broad drainage class in each landscape unit (Figures 7.3 and 7.4). Thus, two soil-landscape units were defined in each model: Dry and Wet units. The composition of the soil-landscape units differs among the models because of the natural difference in the landscape hydrology of the plots rather than because of any harvesting effects. The soil-landscape units of each model formed the basis of the class-based 2 technique used in the spatial prediction of the target soil properties (section 7.2.3).

7.2.1.6 Impacts of forest harvesting on the predictive performance of qualitative soil-landscape modelling (Objective 1b)

The qualitative soil-landscape models were applied to predict the spatial distribution of the broad soil drainage classes within their respective plots. The models were also validated to assess and compare their predictive performance. Both models were found to have performed well. The pre-harvested model correctly predicted broad drainage class at 82% of the validation points whereas the post-harvested model made correct predictions at 85% of the validation points.

Furthermore, the results indicated that, despite a minor alteration to the soil-landscape relationships, forest harvesting had no detrimental impact on the predictive performance of qualitative soil-landscape modelling in southern Mahurangi Forest.

7.2.2 Impacts of forest harvesting on soil properties and their relationship to soil drainage classes and the landscape

The impacts of forest harvesting on (a) the magnitude and variance of the target soil properties and on (b) the relationships between the target soil properties and the soil drainage classes (modified and broad), landscape units, soil-landscape units, and terrain attributes were determined in order to understand better the impacts of harvesting on the predictive performance of quantitative soil-landscape modelling (among other approaches) in southern Mahurangi Forest.

7.2.2.1 Impacts of forest harvesting on the magnitude and variance of the target soil properties (Objective 2a)

Forest harvesting was found to have had a significant impact on the magnitude of all target properties (Table 7.2).

Table 7.2. Mean and variance values of the target properties in both plots. Mean and variance values followed by the same letter are not significantly different ($P < 0.05$).

Property†	Plot‡	Mean*	Variance*
Topsoil pH	Pre	4.98 a	0.09 a
	Post	4.83 b	0.07 b
Mg (cmol$_c$/kg)^1	Pre	2.99 a	0.19 a
	Post	2.60 b	0.13 b
P (ppm)^1	Pre	13.43 a	0.24 a
	Post	18.87 b	0.29 a
K (cmol$_c$/kg)	Pre	0.46 a	0.03 a
	Post	0.56 b	0.02 a
MP (%)	Pre	11.92 a	1.39 a
	Post	9.69 b	1.41 a
TC (%)	Pre	3.62 a	1.50 a
	Post	4.90 b	2.26 b

* Means and variances of soil drainage classes were adjusted (pooled) to remove the effect of drainage class. † MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. ^{1} Geometric means presented.

The means of some target properties (topsoil pH, available Mg, and macroporosity) were significantly decreased whereas the means of other target properties (available P, available K, and total C) were significantly increased after harvesting. The harvesting activities likely to be responsible for the observed affects on the target property means include (1) deposition of organic material (slash), (2) harvesting vehicle trafficking, and (3) land-cover change from mature forest to grassland. The only harvesting effect likely to require a management response was the significant reduction in macroporosity from an adequate to an inadequate level.

The variance of some target properties was also found to have been significantly affected by forest harvesting (Table 7.2). The variance of topsoil pH and available Mg was significantly decreased whereas the variance of total C was significantly increased after harvesting. The patchy nature of slash deposition probably led to the increased variance of total C whereas the change from forest to more uniform grassland vegetation may have reduced the variance of topsoil pH and available Mg. The increased variance of total C probably reduces the accuracy with which this property can be spatially predicted (section 7.2.3).

7.2.2.2 Impacts of forest harvesting on the relationships between the target soil properties and the soil drainage classes and landscape (Objective 2b)

Most target properties were generally strongly related to the modified soil drainage classes and the landscape units in the pre-harvested plot (Table 7.3).

Table 7.3. Mean target property values of the modified soil drainage classes in both plots. Means followed by the same letter are not significantly different ($P < 0.05$).

		Modified soil drainage classes§			
Property†	**Plot‡**	**WD**	**ID**	**SPD**	**PD**
Topsoil pH	Pre	4.75 ab	4.86 b	5.10 c	5.23 c
	Post	4.67 a	4.73 a	4.86 b	5.06 c
Mg (cmol$_c$/kg)^1	Pre	2.15 a	2.20 a	4.07 b	4.14 b
	Post	2.32 a	2.41 a	2.53 ac	3.26 bc
P (ppm)^1	Pre	9.13 a	10.17 a	14.37 b	24.35 d
	Post	14.08 b	14.37 b	17.50 b	35.79 c
K (cmol$_c$/kg)	Pre	0.36 a	0.40 ac	0.54 b	0.52 bc
	Post	0.51 b	0.54 b	0.54 b	0.66 b
MP (%)	Pre	18.08 a	14.00 b	7.71 c	7.89 c
	Post	13.33 b	9.38 c	6.88 c	9.17 bc
TC (%)	Pre	3.83 ac	3.66 ad	3.10 d	3.92 ae
	Post	5.00 b	4.97 b	4.43 bce	5.20 b

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § WD = well drained soils, ID = imperfectly drained soils, SPD = somewhat poorly drained soils, PD = poorly drained soils (defined in Chapter 4, section 4.3.1.2). ^{1} Geometric means presented.

Two distinct groupings of classes/units were evident. For most target properties the Well and Imperfectly Drained soils (also Upper and Middle-H units), had similar means and both were significantly different from those of the Somewhat Poorly and Poorly Drained soils (also Middle-L and Lower units), which tended to be similar. The distinction between the two groups of classes/units also reflected differences in forest management with respect to some target properties (available P, available K, and macroporosity). The means of most target properties (topsoil pH, available Mg, available P, and available K) generally increased down-slope from the drier, more elevated landscape positions to the wetter, less elevated positions and as the soil drainage became more impeded. The patterns of relationships between the target properties and the modified drainage classes were similar to those between the target properties and the landscape units because the modified drainage classes are themselves fairly strongly related to the landscape units in the pre-harvested plot.

Forest harvesting altered and weakened the relationships between most target properties and the modified soil drainage classes and landscape units by altering the means of some classes/units (Table 7.3). Fewer differences in mean values between the classes/units in the post-harvested plot than in the pre-harvested plot are indicative of the weaker relationships. After harvesting, the relationships between the target properties and the modified drainage classes were weaker for all target properties except topsoil pH (made stronger) whereas the relationships between the target properties and the landscape units were weaker for all target properties except total C (made stronger). For some target properties (available P, available K, and macroporosity) the means of the Well and Imperfectly Drained soils were significantly affected by harvesting because these soils occur in upper landscape positions where harvesting disturbance was concentrated. With respect to available Mg and topsoil pH, the means of the Somewhat Poorly Drained soils were significantly affected by harvesting. After harvesting, all modified drainage classes could be managed similarly for all target properties except macroporosity and all landscape units could be managed similarly for all target properties except macroporosity and available K. The soil drainage- and landscape-related trends observed in the pre-harvested plot were essentially the same in the post-harvested plot.

In the pre-harvested plot, most target properties were strongly related to the broad soil drainage classes and the soil-landscape units (Table 7.4).

Table 7.4. Mean target property values of the soil-landscape units in both plots. Means followed by the same letter are not significantly different ($P < 0.05$).

Property†	Plot‡	Soil-landscape units: Dry	Soil-landscape units: Wet
Topsoil pH	Pre	4.77 a	5.16 c
	Post	4.74 a	4.96 b
Mg (cmol$_c$/kg)^1	Pre	2.01 a	4.28 d
	Post	2.40 b	2.84 c
P (ppm)^1	Pre	9.52 a	17.09 b
	Post	14.63 b	25.11 c
K (cmol$_c$/kg)	Pre	0.34 a	0.56 bc
	Post	0.52 b	0.64 c
MP (%)	Pre	15.23 a	9.37 b
	Post	9.91 b	7.70 b
TC (%)	Pre	3.79 a	3.39 a
	Post	4.95 b	4.53 b

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § Dry = dry soil-landscape unit, Wet = wet soil-landscape unit (defined in Chapter 4, section 4.3.3.2).

[1] Geometric means presented.

The Dry class/soil-landscape unit was significantly more acidic, had lower levels of available nutrients (Mg, P, and K) and greater macroporosity than the Wet class/soil-landscape unit. Moreover, the two classes/soil-landscape units could be managed differently with respect to available P, available K, and macroporosity. The soil-landscape units behave similarly to the broad drainage classes because the Wet soil-landscape unit is dominated by Wet soils whereas the Dry soil-landscape unit is dominated by Dry soils.

The relationships between most target properties and the broad drainage classes and soil-landscape units were not altered or weakened by forest harvesting (Table 7.4). However, the means of some classes/units were altered by forest harvesting. After harvesting, the relationships between the target properties and the broad drainage classes remained unchanged for all target properties except available Mg and K (made weaker) whereas the relationships between the target properties and the soil-landscape units remained unchanged for all target properties except macroporosity (made weaker). Thus, the broad drainage classes and soil-landscape units were generally less affected by forest harvesting in terms of the target properties than were the modified drainage classes and the landscape units.

Harvesting resulted in the mean value of the Wet class becoming more like that of the Dry class with respect to available Mg and vice versa with respect to available K. The mean macroporosity of the Dry soil-landscape unit became more like that of the Wet unit after harvesting. After harvesting, both broad drainage classes could be managed similarly for all target properties except macroporosity (adequate in the Dry soils, inadequate in the Wet) whereas both soil-landscape units could be managed similarly for all target properties.

The correlation between the target properties and the terrain attributes was fairly weak in the pre-harvested plot with the multi-linear regression models explaining between 20 and 60% of the variation in most target properties (Table 7.5).

Table 7.5. R^2 values (%) of the regression models and partial R^2 values (%) of their constituent terrain attributes.

		Terrain attributes§						
Property†	**Plot‡**	$\mathbf{Z}$	$\boldsymbol{\beta}$	$\boldsymbol{\Psi}$	$\mathbf{K_{pl}}$	$\mathbf{Z_r}$	W	**Model**
Topsoil pH	Pre	31.4	-	-	5.1	-	-	36.5
	Post	6.5	-	-	-	26.4	-	32.9
Mg (cmol$_c$/kg)	Pre	59.0	-	-	-	-	-	59.0
	Post	-	3.9	-	-	6.2	3.9	14.1
P (ppm)	Pre	26.5	-	9.7	4.1	-	-	40.2
	Post	-	12.0	5.4	-	10.6	-	28.0
K (cmol$_c$/kg)	Pre	22.5	-	-	-	-	-	22.5
	Post	-	-	-	-	14.4	-	14.4
MP (%)	Pre	16.2	11.6	-	-	-	-	27.8
	Post	-	-	-	-	-	-	-
TC (%)	Pre	-	-	-	-	6.7	-	6.7
	Post	-	9.4	-	-	7.4	-	16.8

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § $\mathbf{Z}$ = elevation, $\boldsymbol{\beta}$ = slope steepness, $\boldsymbol{\Psi}$ = aspect, $\mathbf{K_{pl}}$ = plan curvature, $\mathbf{Z_r}$ = relative elevation, W = topographic wetness index, **Model** = multi-linear regression models.

Available Mg was the most strongly correlated target property whereas total C was the least strongly correlated. All target properties except total C were most strongly correlated to elevation. However, aspect, plan curvature, relative elevation, and slope steepness were also correlated to some target properties. Forest harvesting generally weakened the correlations between the target properties and the terrain attributes. The proportion of the variation explained by the multi-linear regression models was lower for all target properties except total C after harvesting. Also, relative elevation surpassed elevation as the terrain attribute most strongly correlated to the majority of target properties after harvesting. The nature of the landscape hydrology of the post-harvested plot is probably responsible for relative elevation being a more important determinant of the target properties than elevation (section 7.2.1.3).

7.2.2.3 Justification for modifying the soil drainage classes

The separation of the existing imperfectly drained soils (predominantly Mottled Yellow Ultic Soils) into two classes – Imperfectly Drained and Somewhat Poorly Drained (section 7.2.1.1) – was found to be appropriate and effective. In the pre-harvested plot, the means of the Imperfectly Drained soils were significantly different from those of the Somewhat Poorly Drained soils for all target properties except total C (Table 7.3). Moreover, the two classes could be managed differently with respect to available P, Mg, and K. It is recommended that the New Zealand soil drainage criteria be modified by placing greater emphasis on the abundance of, and depth to, redox depletions within the profile. The difference in drainage class within the Mottled Yellow Ultic subgroup could be communicated at the soilform level if the revised soil drainage criteria were incorporated into the soilform (replacing the permeability classes).

7.2.3 Spatial prediction of soil properties: impacts of forest harvesting on a range of prediction techniques

The impacts of forest harvesting on the performance of seven techniques representing the class-based, quantitative soil-landscape modelling, and geostatistical approaches to the spatial prediction of target soil properties were determined in southern Mahurangi Forest.

7.2.3.1 General comparison of predictive performance

All prediction techniques gave fairly unbiased predictions ($-1 <$ mean error < 1). Moreover, all techniques gave similarly unbiased predictions of most target soil properties in either pre- or post-harvested plots (Chapter 6, Table 6.4). The accuracy of all techniques (including the reference) was also reasonably similar for most target soil properties in either plot (Chapter 6, Table 6.5). However, the geostatistical and quantitative soil-landscape modelling techniques (ordinary kriging, regression kriging, and multi-linear regression) and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques (class-based 2 and 4) tended to be slightly more precise than the other class-based and reference techniques. A corollary of the similarity in accuracy was that, in general, most techniques were not substantially more precise than the sample mean (reference technique) (Table 7.6). However, in some instances, the geostatistical and quantitative soil-landscape modelling techniques and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques did offer substantial improvements in accuracy over that of the sample mean. In concurrence with the bias and accuracy results, the assessment of relative performance indicated that the accuracy and consistency of all techniques was fairly similar — the range in mean rank and standard deviation of rank values for all target soil properties in either plot was reasonably narrow.

Therefore, within a given plot, the performance of all prediction techniques (including the reference) was generally similar for all target soil properties. However, the geostatistical and quantitative soil-landscape modelling techniques, and, to a lesser extent, the semi-quantitative soil-landscape modelling techniques tended to be slightly more accurate than the less sophisticated techniques and tended to offer a greater improvement over the sample mean. On the other hand, the majority of class-based techniques tended to be more consistent than the more sophisticated techniques.

7.2.3.2 Impacts of forest harvesting on the performance of seven techniques for the spatial prediction of target soil properties (Objective 3)

A comparison of the pre- and post-harvested plots revealed that most of techniques used gave less biased predictions of most target soil properties after forest harvesting, and that prior to harvesting most predictions were under-estimates whereas after harvesting most predictions were over-estimates. Furthermore, it was found that the predictions of most techniques were slightly less precise after harvesting for most target soil properties. In some cases, the reduction in the accuracy of predictions could be attributed to the weakening of some relationships between the target soil properties and the soil drainage classes (modified and broad), landscape units, and terrain attributes caused by forest harvesting (section 7.2.2.2). However, in most cases the reduction (or increase) in accuracy could not be explained by the harvesting-related changes to the predictive relationships. For total C, the reduction in accuracy was probably due largely to the increase in the variance of that property caused by forest harvesting. The prediction accuracy of most techniques increased after harvesting for available Mg and P. For these properties, the increase in accuracy was attributed to a decrease in variance which may have been caused by the change in vegetation cover that necessarily resulted from forest harvesting.

Most prediction techniques offered less improvement in accuracy over the sample mean after harvesting for most target soil properties (Table 7.6). Therefore, most techniques became relatively less useful after harvesting.

Table 7.6. Goodness-of-prediction (G) of prediction techniques in both plots (%).

		Prediction technique§						
Property†	**Plot‡**	**CB1**	**CB2**	**CB3**	**CB4**	**MLR**	**RK**	**OK**
Topsoil pH	Pre	21.70	37.62	19.65	31.08	27.29	30.53	33.75
	Post	17.33	17.48	21.98	18.40	33.20	33.20	23.64
Mg	Pre	15.84	43.22	15.23	42.98	30.01	49.68	57.64
	Post	8.99	10.11	13.28	1.65	-2.33	-	13.52
P	Pre	18.56	14.01	17.51	11.50	7.64	10.48	22.57
	Post	6.54	2.26	2.03	2.53	3.43	4.58	13.53
K	Pre	-3.79	12.38	-5.55	13.95	19.10	26.31	28.61
	Post	4.04	13.27	5.18	19.22	21.38	24.81	16.41
MP	Pre	23.36	5.49	20.47	2.57	1.32	4.28	12.64
	Post	5.38	3.24	0.87	10.67	-	-	-15.52
TC	Pre	5.68	6.73	-4.31	10.46	17.13	31.97	26.88
	Post	0.31	3.62	-3.10	10.39	16.96	11.95	9.34

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § CB1 = class-based technique 1, CB2 =class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging.

The reduction in the goodness-of-prediction values after harvesting occurred because the accuracy of the reference technique either was decreased by less than that of the other techniques or it was increased by more than that of the other techniques. In some cases (e.g. available K) the goodness-of-prediction values of some techniques increased after harvesting. This increase was caused by the accuracy of the reference technique being decreased by more than that of the other techniques. The weakening of some predictive relationships by forest harvesting (section 7.2.2.2) explained the reduction in relative accuracy in some cases but not others.

In terms of the comparison of relative performance between the plots, it was found that no one prediction technique performed best for all target soil properties in either plot. However, half of the target soil properties in the pre-harvested plot were best predicted by ordinary kriging whereas half of the target soil properties in the post-harvested plot were best predicted by the class-based 2 technique. Furthermore, some general effects of forest harvesting were identified in considering all target soil properties together (Figure 7.5).

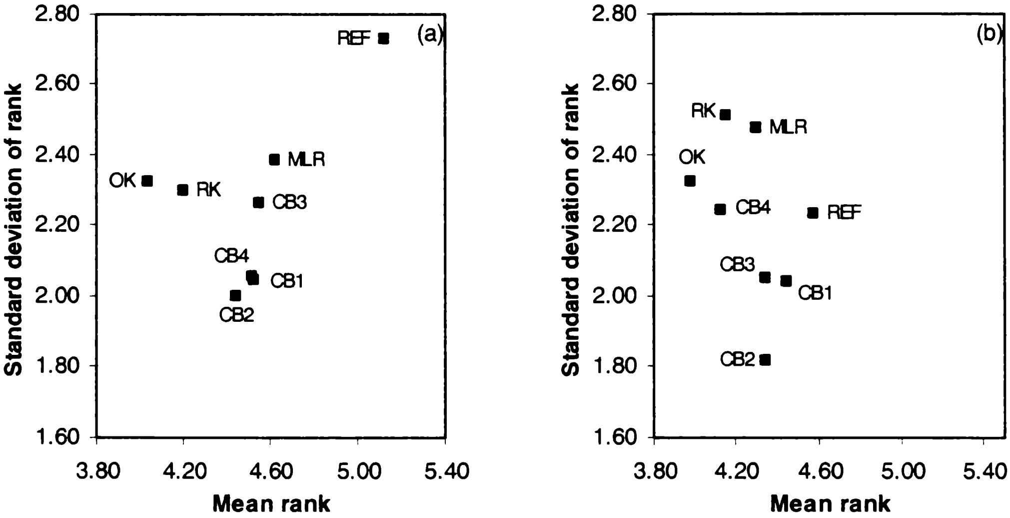


Figure 7.5. MR and SDR of techniques used to predict all target properties in the (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

After forest harvesting, the relative performance of some prediction techniques (regression kriging and ordinary kriging) generally became poorer whereas the relative performance of other techniques (class-based 2, class-based 3, and class-based 4) generally improved. On balance, the relative performances of the class-based 1, multi-linear regression, and reference techniques remained the same. The prediction techniques that showed an improvement in relative performance after harvesting (e.g. the semi-quantitative soil-landscape models) were generally more resilient to the disturbance caused by forest harvesting than were the other techniques (e.g. regression kriging) because of the nature of the relationships on which their predictions were based. However, the weakening of some of these predictive relationships by forest harvesting did not impair the relative performance of some techniques (class-based 3 and 4).

In summary, ordinary kriging (the geostatistical technique) is the best predictor of target soil properties in the pre-harvested areas of southern Mahurangi Forest whereas the class-based 2 technique (a semi-quantitative soil-landscape model) is the best within the post-harvested areas. Furthermore, the class-based 2 technique has the potential to offer a more practical and cost-effective alternative to ordinary kriging throughout the forest because it can be applied using the landscape. However, the performance of the class-based 2 technique is very much dependent on the development of accurate qualitative soil-landscape models. The other techniques (e.g. the quantitative soil-landscape models) either failed to perform well after harvesting or were likely to be less cost-effective, or both.

7.3 Conclusions

The main conclusions of the research relating to the specific objectives given in Chapter 1 (section 1.3) are as follows.

1. Hauler-based, clear-fell, forest harvesting did not (a) substantially alter or weaken the relationships between the soil drainage classes and the landscape units, nor did it (b) have any detrimental impact on the performance of the qualitative soil-landscape modelling approach to the spatial prediction of soil drainage classes in southern Mahurangi Forest.

2. Hauler-based, clear-fell, forest harvesting (a) significantly altered the magnitude of all target soil properties and the variance of some target soil properties, and (b) altered and weakened the relationships between most target soil properties and the modified soil drainage classes, landscape units, and terrain attributes. However, forest harvesting did not alter or weaken the relationships between most target soil properties and the broad

soil drainage classes and soil-landscape units in southern Mahurangi Forest.

3. Considering all target soil properties together, hauler-based, clear-fell, forest harvesting had a detrimental impact on the relative performance of some techniques (regression-kriging and ordinary kriging), a neutral impact on the relative performance of other techniques (multi-linear regression and class-based 1), and a beneficial impact on the relative performance of the remaining techniques (class-based 2, 3, and 4) for the spatial prediction of target soil properties in southern Mahurangi Forest.

4. Considering all target soil properties together, the geostatistical technique (ordinary kriging) was the best predictor prior to forest harvesting whereas a semi-quantitative soil-landscape modelling technique (class-based 2) was the best after harvesting. However, most techniques generally gave less precise predictions of most target properties after harvesting.

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APPENDIX ONE

Key soil profile descriptions

The key soil profile description data collected for the study are presented below[1]. For each description, the reference data are given first, then information describing the nature of the site, and finally the soil morphological data are given (following Clayden and Hewitt, 1994; Milne *et al.*, 1995; modified drainage classes are defined in Chapter 4, section 4.3.1.2). Penetration resistance was measured using a hand-held, 6.5 mm flat-tipped penetrometer and degree of packing was determined using the semi-confined, single-vane test of Griffiths (1985). Soil pH was measured in H_20 according to the method of Blakemore *et al.* (1987) and particle size was determined using the pipette method as described by Claydon (1989). The land management practices of grazing and fertilization have probably been applied to all sites in the past (whilst under pastoral farming). For all pedons the vegetation structural class is forest and the land-use class is production forestry. Note that as part of the geomorphic description, slope shape is given in the format of profile/contour (e.g. linear/convex) and that all aspects and directions are given in degrees relative to grid north. The land elements and sub-elements are defined in Chapter 4, section 4.3.2.1 and are summarised here by Figure A1.1. Soil names (series) and parent materials are further discussed in Chapter 3 and soil classifications follow Hewitt (1998), Clayden and Webb (1994), and Soil Survey Staff (1999).

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[1] Only the key profiles are recorded here. Additional profiles were described either from pits or sections or from augering during the course of the project, and the findings have been incorporated into various chapters in the thesis. Seven additional profile descriptions are available from the author on request.

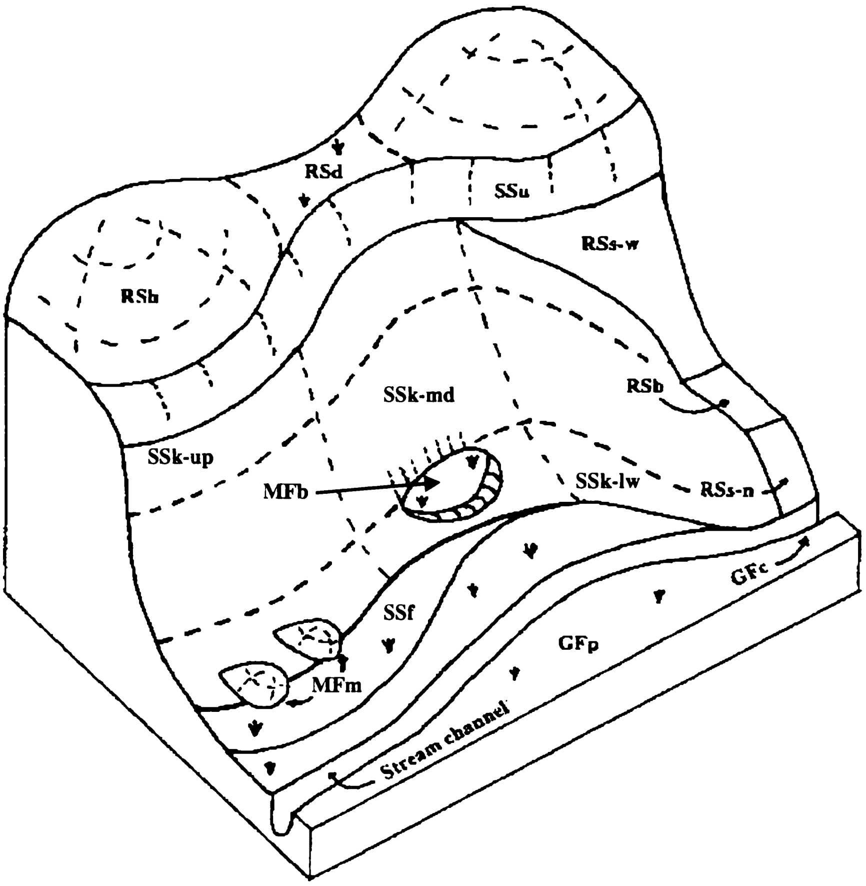

Figure A1.1. An idealised block diagram illustrating the nature and position of the land elements and sub-elements within both plots. Key: RSs-n = narrow ridge summit slopes, RSs-w = wide ridge summit slopes, RSb = ridge summit bench, RSh = ridge summit hillock, RSd = ridge summit saddle, SSu = side-slope shoulder, SSk-up = upper side-slope back-slope, SSk-md = middle side-slope back-slope, SSk-lw = lower side-slope back-slope, SSf = side-slope foot-slope, GFp = gully floor floodplain, GFc = gully floor channel, MFm = mudslide feature mound, MFb = mudslide feature bench.

Profile 1

Reference Data

- Land element/sub-element: RSb
- Soil name:
  - Series: Warkworth
- Soil classification:
  - NZSC: Typic Yellow Ultic Soil; Md; C; s
  - Soil Taxonomy: Typic Hapludults

Site Data

- Location:
  - Map reference: NZMS 260 R09 54350 24050
  - Word description: 190 m northeast (25°) of the end of Barker Road
- Elevation: 270 m
- Geomorphic position: Profile on a 3° convex/convex bench with 141° aspect contained within the summit of a spur ridge in hill country
- Erosion/Deposition: Nil
- Vegetation: Mature *Pinus radiata*, grasses, and bracken fern

- Parent material: Reddish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group)
- Modified drainage class: Well Drained

Soil Data

Ah 0-10 cm	Dry; dark yellowish brown (10YR 3/4) loamy clay (59% clay, 15% sand); moderately sticky; very plastic; peds slightly firm and brittle; high penetration resistance (2645.5 kPa); very high packing (3532.1 kPa); moderately pedal; 60% fine blocky to polyhedral peds; common very fine roots, few fine to medium roots, and common microfine to extremely fine roots; non allophanic; pH 4.84; distinct smooth boundary.
Bt 10-29 cm	Slightly moist; yellowish brown (10YR 5/6) clay (65% clay, 13% sand); moderately sticky; very plastic; peds slightly firm and brittle; high penetration resistance (2416.7 kPa); very high packing (3732.3 kPa); 3% fine infilled channels; moderately pedal; 30% medium and 35% fine blocky to polyhedral peds; 40% distinct clay coats lining voids and on ped surfaces; few fine and very fine roots; non allophanic; pH 4.90; indistinct smooth boundary.
Btv 29-53 cm	Slightly moist; yellowish brown (10YR 5/8) loamy clay (58% clay, 18% sand); 10% very fine prominent yellowish red (5YR 5/8) mottles (differential weathering); moderately sticky; very plastic; peds slightly firm and brittle; moderate penetration resistance (2059.2 kPa); extremely high packing (5720 kPa); weakly pedal; 15% fine blocky to polyhedral peds; 50% distinct clay coats lining voids and on ped surfaces; few extremely fine and fine roots; non allophanic; pH 4.68; diffuse smooth boundary.
Cu1 53-87 cm	Slightly moist; yellowish red (5YR 5/7) loamy clay (37% clay, 34% sand); 3% fine to very fine dark reddish brown (5YR 2/2) manganese segregations (inherited); slightly sticky; very plastic; soil weak and friable; low penetration resistance (1444.3 kPa); extremely high packing (4161.3 kPa); apedal massive; few fine roots; non allophanic; pH 4.49; diffuse smooth boundary.
Cu2 87-122 cm	Red (2.5YR 5/8) and red to yellowish red (2.5YR/5YR 5/6) silty clay; 5% fine to very fine dark reddish brown (5YR 2/2) manganese segregations (inherited); moderately sticky; very plastic; soil slightly firm and semi-deformable; apedal massive; non allophanic; diffuse smooth boundary.
Cu3 122 cm - on	Yellowish red (5YR 5/8) loamy clay; 5% fine to very fine dark reddish brown (5YR 2/2) manganese segregations (inherited); very weakly indurated; apedal massive; non allophanic.

Profile 2

Reference Data

- Land element/sub-element: RSs-w
- Soil name:
  - Series: Whangaripo
- Soil classification:
  - NZSC: Mottled Yellow Ultic Soil; Md; C; s
  - Soil Taxonomy: Typic Hapludults

Site Data

- Location:
  - Map reference: NZMS 260 R09 54425 23975
  - Word description: 175 m northeast (35°) of the end of Barker Road
- Elevation: 250 m
- Geomorphic position: Profile on a 12° linear/convex slope with 171° aspect contained within the summit of a spur ridge in hill country
- Erosion/Deposition: Nil
- Vegetation: Mature *Pinus radiata*, grasses, and bracken fern
- Parent material: Reddish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group)
- Modified drainage class: Imperfectly Drained

Soil Data

Ah

0-16 cm Dark yellowish brown (10YR 4/4) silty clay; moderately sticky; very plastic; peds slightly firm and brittle; high penetration resistance (2416.7 kPa); high packing (2874.3kPa); 4% fine infilled channels; moderately pedal; 50% fine polyhedral peds and 10% medium polyhedral peds; common microfine roots and few extremely fine roots; non allophanic; pH 4.91; indistinct smooth boundary.

Bt(f)

16-35 cm Yellowish brown (10YR 5/4) silty clay; 5% very fine prominent yellowish red (5YR 5/8) mottles and 10% very fine prominent reddish yellow (5YR 6/8) mottles; moderately sticky; very plastic; peds firm and brittle; high penetration resistance (2531.1 kPa); extremely high packing (4604.6 kPa); moderately pedal; 60% fine polyhedral peds and 8% medium polyhedral peds; 20% faint clay lining voids and on ped faces; common microfine roots and few extremely fine roots; non allophanic; pH 4.81; indistinct smooth boundary.

Bt(f)v

35-68 cm Yellowish brown (10YR 5/6) silty clay; 20% very fine yellowish red (5YR 5/8) mottles, 5% extremely fine prominent light greenish grey (7.5GY 8/1) mottles (differential weathering), and 10% very fine reddish yellow (5YR 6/8) mottles; moderately sticky; very plastic; peds slightly firm and semi-deformable; low penetration resistance (1229.8 kPa); extremely high packing (4547.4 kPa); weakly pedal; 15% fine polyhedral peds; 25% faint clay coats lining voids and on ped faces; common very fine roots and common microfine roots; non allophanic; pH 4.94; indistinct smooth boundary.

BCt(f)v

68-98 cm Brownish yellow (10YR 6/6) silty clay; 10% extremely fine prominent red (2.5YR 4/8) mottles (differential weathering), 40% fine to medium prominent light red (2.5YR 6/6) mottles (differential weathering), 5% extremely fine prominent light greenish grey (7.5GY 8/1) mottles (differential weathering), and 8% extremely fine to very fine prominent yellowish red (5YR 5/8) mottles; slightly sticky; very plastic; soil weak and semi-deformable; very low penetration resistance (757.9 kPa); very high packing (3403.4 kPa); apedal massive; 40% distinct clay coats lining voids and on ped faces; non allophanic; pH 4.64; indistinct smooth boundary.

Cu

98 cm - on Red (2.5YR 5/7) silty clay; moderately sticky; very plastic; soil weak and semi-deformable; apedal massive; non allophanic; pH 4.60.

Profile 3

Reference Data

- Land element/sub-element: SSk-lw
- Soil name:
    - Series: Puhoi
- Soil classification:
    - NZSC: Mottled Yellow Ultic Soil; Md; C; s
    - Soil Taxonomy: Aeric Endoaquults

Site Data

- Location:
    - Map reference: NZMS 260 R09 54325 23800
    - Word description: 20 m northwest (288.5°) of the end of Barker Road
- Elevation: 230 m
- Geomorphic position: Profile on a 13.5° concave/linear slope with 351° aspect contained within the upper back-slope of a side-slope in hill country
- Erosion/Deposition: Nil
- Vegetation: Mature *Pinus radiata*, coprosma, hook-grass, and bracken fern
- Parent material: Yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group)
- Modified drainage class: Somewhat Poorly Drained

Soil Data

Ah

0-10 cm Dry; dark brown (10YR 4/3) and yellowish brown (10YR 5/4) loamy clay (55% clay, 18% sand); moderately sticky; very plastic; peds slightly firm and brittle; high penetration resistance (2888.6 kPa); medium packing (2016.3 kPa); 1% 10 mm channels; weakly pedal; 17% fine polyhedral peds and 3% medium polyhedral peds; few microfine to extremely fine roots and few very fine roots; non allophanic; abrupt wavy boundary.

Bt(g)1

10-21 cm Slightly moist; light yellowish brown (2.5Y 6/4) and yellowish brown (10YR 5/4) clay (60% clay, 17% sand); 8% extremely fine to very fine prominent yellowish red (5YR 5/8 and 5YR 4/8) mottles and 5% very fine to fine distinct pale olive (5Y 6/3) mottles; very sticky; very plastic; peds firms and brittle; very high penetration resistance (3660.8 kPa); extremely high packing (5720 kPa); 1% 6 mm infilled channels; moderately pedal; 20% fine polyhedral peds and 10% medium blocky peds; 35% distinct patchy clay coats infilling voids and on ped faces; common microfine roots and few extremely fine to medium roots; weakly allophanic; indistinct smooth boundary.

Bt(g)2
21-38 cm Slightly moist; light yellowish brown (2.5Y 6/4) and pale olive (5Y 6/4) loamy clay (59% clay, 16% sand); 10% very fine to fine prominent yellowish red (5YR 4/8, 4/6, and 5/8) mottles and 8% very fine distinct light grey (10Y 7/1) and pale olive (5Y 6/3) mottles; very sticky; very plastic; peds firm and brittle; high penetration resistance (2516.8 kPa); extremely high packing (5720 kPa); moderately pedal; 50% medium blocky peds, 10% coarse blocky peds, and 5% fine polyhedral peds; 70% distinct continuous clay coats lining voids and on ped faces; common microfine roots and few extremely fine and very fine roots; moderately allophanic; pH 5.04; distinct smooth boundary.

Bt(g)3
38-56 cm Slightly moist; yellow (2.5Y 7/6) and light yellowish brown (2.5Y 6/4) silty clay; 20% fine to medium prominent yellowish red (5YR 5/8 and 4/6) mottles and 10% very fine distinct light grey (10Y 7/1) mottles; moderately sticky; very plastic; peds slightly firm and brittle; high penetration resistance (2459.6 kPa); extremely high packing (5720 kPa); weakly pedal; 10% fine blocky to polyhedral peds and 10% medium blocky to polyhedral peds; 80% distinct continuous clay coats lining voids and on ped faces; few extremely fine and fine roots; non allophanic; pH 4.90; indistinct smooth boundary.

BC(f)
56 cm – on Slightly moist; yellowish brown (10YR 5/8) loamy clay; 2% very fine distinct yellowish red (5YR 5/8) mottles; slightly sticky; moderately plastic; soil slightly firm and brittle; very high penetration resistance (3246.1 kPa); extremely high packing (5720 kPa); apedal massive; non allophanic.

Profile 4

Reference Data

- Land element/sub-element: MFb
- Soil name:
  - Series: Pohuehue (proposed)
- Soil classification:
  - NZSC: Typic Perch-gley Ultic Soil; Md; C; s/m
  - Soil Taxonomy: Aeric Epiaquults

Site Data

- Location:
  - Map reference: NZMS 260 R09 54575 23800
  - Word description: 140 m northwest (299°) of the culvert under Barker Road (through which Hungry Creek flows)
- Elevation: 200 m
- Geomorphic position: Profile on a 9° concave/convex slope with 101° aspect contained within the bench of a landslide feature in hill country
- Erosion/Deposition: Nil
- Vegetation: Mature *Pinus radiata*, Nikau palms, low shrubs, and bracken fern
- Parent material: Yellowish saprolite derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group)
- Modified drainage class: Poorly Drained

Soil Data

Ah

0-10 cm Moderately moist; light olive brown (2.5Y 5/3) loamy clay; 3% extremely fine prominent reddish yellow (5YR 6/8) mottles; moderately sticky; very plastic; peds weak and semi-deformable; extremely low penetration resistance (274.7 kPa); medium packing (1393.6 kPa); 5% fine infilled channels; weakly pedal; 15% fine polyhedral peds and 5% medium polyhedral peds; common very fine roots and few medium and extremely fine roots; non allophanic; distinct wavy boundary.

Btg

10-25 cm Moderately moist; pale olive (5Y 6/3) silty clay; 20% fine prominent yellowish red (5YR 5/8) mottles; very sticky; very plastic; peds slightly firm and semi-deformable; very low penetration resistance (603 kPa); high packing (2745.6 kPa); 3% fine infilled channels; moderately pedal; 25% fine polyhedral to blocky peds and 10% medium polyhedral to blocky peds; 50% distinct patchy thick clay coats lining voids and on ped faces; common extremely fine and very fine roots; non allophanic; pH 5.39; abrupt wavy boundary.

Bt(g)

25-45 cm Slightly moist; yellowish brown (10YR 5/6) loamy clay; 8% very fine to fine prominent light grey (7.5Y 7/2.5) mottles, 4% very fine to fine prominent red (2.5YR 5/6) mottles, and 2% very fine prominent yellowish red (5YR 5/8) mottles; moderately sticky; very plastic; peds slightly firm to weak and semi-deformable; very low penetration resistance (636.5 kPa); medium packing (2173.6 kPa); weakly pedal; 20% fine polyhedral peds and 40% very fine polyhedral peds; 40% distinct patchy thick clay coats lining voids and on ped faces; 5% very fine black (10YR 1.7/1) manganese segregations; few extremely fine and very fine roots; non allophanic; pH 5.43; indistinct smooth boundary.

BCt(g)

45 cm – on Slightly moist; yellowish brown (10YR 5/6) loamy clay; 5% very fine to fine prominent light grey (7.5Y 7/2.5) mottles; moderately plastic; very sticky; peds weak and friable; very low penetration resistance (562.8 kPa); medium packing (1587.3 kPa); apedal earthy; 50% very fine polyhedral peds; 40% distinct patchy thick clay coats lining voids and on ped faces; non allophanic.

Profile 5

Reference Data

- Land element/sub-element: GFc
- Soil name:
  - Series: Kara
- Soil classification:
  - NZSC: Argillic Orthic Gley Soil; Md; L/C; m
  - Soil Taxonomy: Typic Endoaquults

Site Data

- Location:
  - Map reference: NZMS 260 R09 54625 23750
  - Word description: 80 m northwest (286.5°) of the culvert under Barker Road (through which Hungry Creek flows)
- Elevation: 180 m
- Geomorphic position: Profile on a 1° linear/concave slope with 126° aspect contained within the channel of a gully floor in hill country
- Erosion/Deposition: Nil
- Vegetation: Mature *Pinus radiata*, cutty-grass, coprosma, and bracken fern
- Parent material: Yellowish saprolitic colluvium derived from the strongly weathered sandstones and siltstones of the Pakiri Formation (Waitemata Group)
- Modified drainage class: Poorly drained

Soil Data

Ah

0-16 cm Moderately moist; dark brown (10YR 3/3) and dark yellowish brown (10YR 4/4) sandy clay loam; slightly sticky; very plastic; peds very weak and friable; very low penetration resistance (515.9); medium packing (1011.7 kPa); 5% fine infilled channels; apedal earthy; 70% very fine polyhedral peds; many very fine and fine roots and few medium roots; non allophanic; abrupt smooth boundary.

Bt(g)

16-25 cm Moderately moist; yellowish brown (10YR 5/4) loamy clay; 35% fine prominent pale olive (5Y 6/3) mottles and 5% very fine prominent yellowish red (5YR 5/8) mottles; moderately sticky; very plastic; peds weak and friable; very low penetration resistance (723.6 kPa); medium packing (1467.3 kPa); 3% fine infilled channels; weakly pedal; 15% fine polyhedral peds and 5% medium polyhedral peds; 30% distinct patchy thick clay coats lining voids and on ped faces; common very fine roots and few microfine and extremely fine roots; very weakly allophanic; distinct smooth boundary.

Btg
25-52 cm Moderately moist; greyish olive (7.5Y 6/2) silty clay with 2% coarse subrounded very highly weathered gravel; 15% very fine prominent yellowish red (5YR 4/8 and 5/8) mottles; very sticky; very plastic; peds slightly firm and semi-deformable; very low penetration resistance (710.2 kPa); medium packing (1621.4 kPa); 1% medium infilled channels; moderately pedal; 5% fine polyhedral peds and 10% medium polyhedral peds; 55% distinct patchy thick clay coats lining voids and on ped faces; few very fine, microfine, and extremely fine roots; very weakly allophanic; pH 5.55; indistinct smooth boundary.

Cr
52 cm – on Very moist; light greenish grey (2.5GY 7/1) clay; 10% fine to medium prominent strong brown (7.5YR 5/8) mottles; very sticky; very plastic; soil weak and deformable; very low penetration resistance (542.7 kPa); medium packing (1916.2 kPa); 2% extremely fine tabular voids; apedal massive; 70% distinct continuous thick clay coats; few microfine and very fine roots; non allophanic.

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APPENDIX TWO

Predicted spatial distribution of broad soil drainage classes across southern Mahurangi Forest

The spatial distribution of the broad soil drainage classes was predicted across southern Mahurangi using a simplified version of the pre-harvested qualitative soil-landscape model (Chapter 4, section 4.2.4.3). The simplified pre-harvested plot model predicted broad drainage class on the basis of relative elevation class alone. That is, where the relative elevation class was high, Dry soils were predicted, and where the relative elevation class was low, Wet soils were predicted. A simplified version of the pre-harvested model was used because it could be rapidly and conveniently applied across the forest. The method used to develop this map was described in Chapter 4 (section 4.2.6).

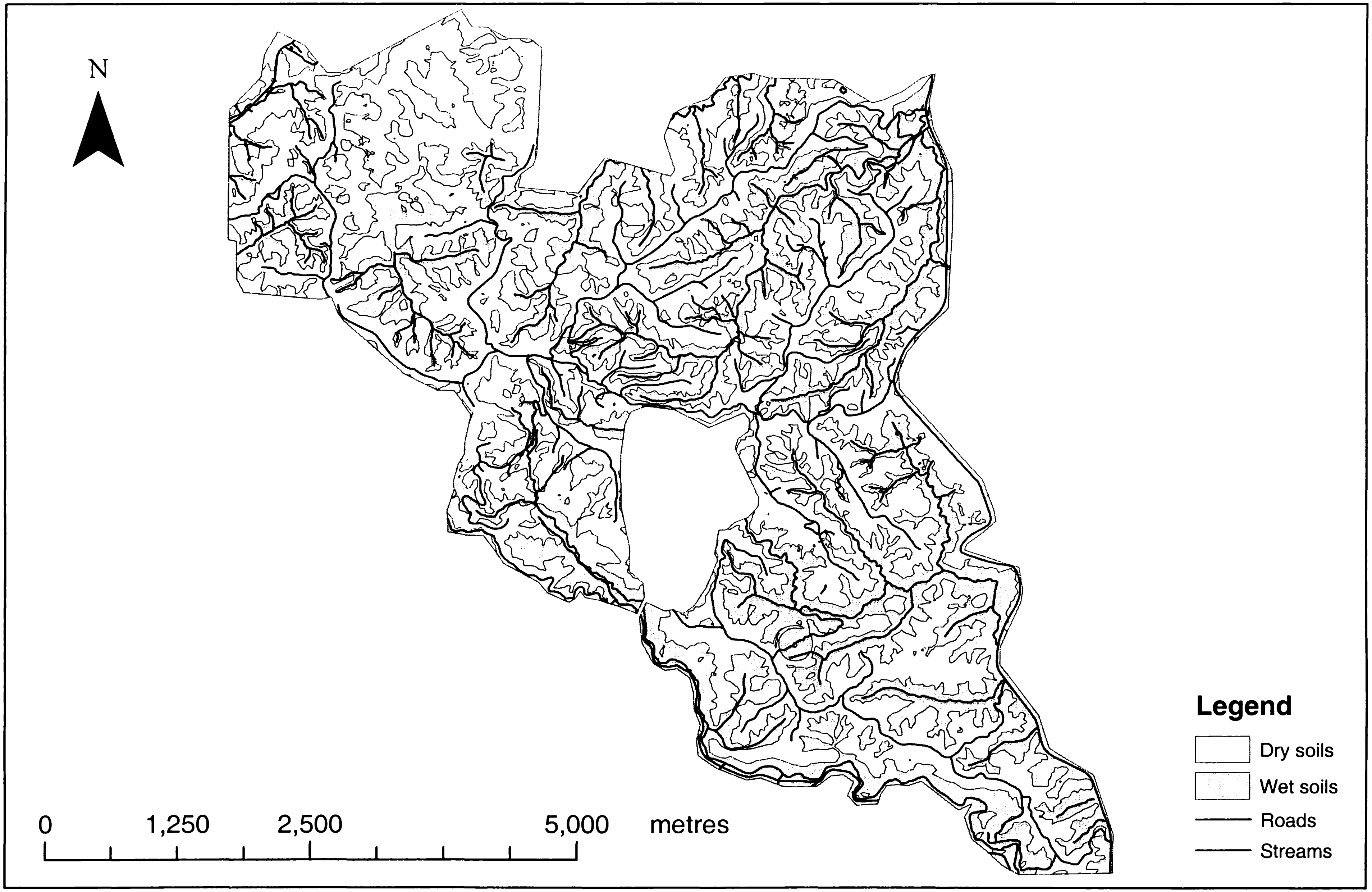

Figure A2.1. Map showing the predicted spatial distribution of broad soil drainage classes across southern Mahurangi Forest

APPENDIX THREE

Summary statistics of soil property predictions

Table A3.1. Summary statistics of predicted and observed soil property values (topsoil pH and available Mg) at the validation points of both plots.

			Statistic				
Soil Property†	**Technique§**	**Plot‡**	**Mean**	**Median**	**Variance**	**Min**	**Max**
pH	OBS	Pre	4.92	4.87	0.07	4.41	5.82
		Post	4.77	4.77	0.08	4.11	5.38
	CB1	Pre	4.95	4.79	0.03	4.79	5.15
		Post	4.75	4.72	0.01	4.72	4.91
	CB2	Pre	4.96	4.77	0.04	4.77	5.16
		Post	4.78	4.74	0.01	4.74	4.96
	CB3	Pre	4.95	4.86	0.03	4.75	5.23
		Post	4.76	4.73	0.01	4.67	5.06
	CB4	Pre	4.97	4.84	0.04	4.70	5.25
		Post	4.77	4.83	0.02	4.56	4.96
	MLR	Pre	4.95	4.97	0.06	4.50	5.41
		Post	4.77	4.81	0.03	4.44	5.08
	RK	Pre	4.95	4.95	0.07	4.49	5.62
		Post	4.76	4.81	0.04	4.36	5.14
	OK	Pre	4.92	4.94	0.05	4.53	5.45
		Post	4.77	4.79	0.03	4.37	5.17
	REF	Pre	4.96	4.96	0.00	4.96	4.96
		Post	4.78	4.78	0.00	4.78	4.78
Mg (cmol$_c$/kg)*	OBS	Pre	1.12	1.09	0.26	0.19	2.15
		Post	0.89	0.87	0.13	-0.12	1.83
	CB1	Pre	1.05	0.77	0.10	0.77	1.41
		Post	0.89	0.87	0.00	0.87	1.00
	CB2	Pre	1.06	0.70	0.15	0.70	1.45
		Post	0.91	0.88	0.00	0.88	1.04
	CB3	Pre	1.05	0.79	0.10	0.76	1.42
		Post	0.90	0.88	0.01	0.84	1.18
	CB4	Pre	1.07	0.72	0.15	0.67	1.47
		Post	0.90	0.97	0.02	0.71	1.04
	MLR	Pre	1.05	1.11	0.20	0.17	1.87
		Post	0.89	0.94	0.05	0.46	1.26
	RK	Pre	1.03	1.05	0.20	0.19	1.88
		Post	-	-	-	-	-
	OK	Pre	1.03	0.99	0.20	0.22	1.93
		Post	0.91	0.92	0.03	0.61	1.39
	REF	Pre	1.07	1.07	0.00	1.07	1.07
		Post	0.91	0.91	0.00	0.91	0.91

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § OBS = observed mean, CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based

technique 3, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique. * Summary statistics of transformed data presented.

Table A3.2. Summary statistics of predicted and observed soil property values (available P and K) at the validation points of both plots.

					Statistic		
Soil Property†	**Technique§**	**Plot‡**	**Mean**	**Median**	**Variance**	**Min**	**Max**
P (ppm)*	OBS	Pre	2.57	2.53	0.38	1.46	4.20
		Post	2.75	2.65	0.28	1.74	4.11
	CB1	Pre	2.52	2.26	0.09	2.26	2.87
		Post	2.73	2.66	0.02	2.66	3.06
	CB2	Pre	2.54	2.25	0.09	2.25	2.84
		Post	2.79	2.68	0.05	2.68	3.22
	CB3	Pre	2.52	2.32	0.11	2.21	3.19
		Post	2.74	2.67	0.05	2.65	3.58
	CB4	Pre	2.56	2.25	0.15	2.25	3.20
		Post	2.77	2.70	0.06	2.57	3.22
	MLR	Pre	2.51	2.49	0.15	1.82	3.46
		Post	2.78	2.75	0.08	2.34	3.49
	RK	Pre	2.49	2.49	0.16	1.82	3.35
		Post	2.76	2.74	0.10	2.00	3.51
	OK	Pre	2.50	2.48	0.11	1.84	3.24
		Post	2.73	2.71	0.08	2.25	3.35
	REF	Pre	2.54	2.54	0.00	2.54	2.54
		Post	2.79	2.79	0.00	2.79	2.79
K (cmol$_c$/kg)*	OBS	Pre	0.66	0.66	0.02	0.31	0.99
		Post	0.72	0.73	0.02	0.36	1.05
	CB1	Pre	0.64	0.60	0.00	0.60	0.71
		Post	0.72	0.71	0.00	0.71	0.74
	CB2	Pre	0.65	0.57	0.01	0.57	0.73
		Post	0.72	0.71	0.00	0.71	0.78
	CB3	Pre	0.65	0.62	0.00	0.58	0.71
		Post	0.72	0.72	0.00	0.70	0.79
	CB4	Pre	0.64	0.60	0.01	0.55	0.77
		Post	0.72	0.75	0.00	0.62	0.78
	MLR	Pre	0.64	0.66	0.01	0.46	0.81
		Post	0.72	0.72	0.00	0.61	0.84
	RK	Pre	0.65	0.66	0.01	0.48	0.82
		Post	0.72	0.72	0.01	0.59	0.87
	OK	Pre	0.66	0.66	0.01	0.50	0.83
		Post	0.72	0.72	0.00	0.61	0.88
	REF	Pre	0.65	0.65	0.00	0.65	0.65
		Post	0.72	0.72	0.00	0.72	0.72

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § OBS = observed mean, CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique. * Summary statistics of transformed data presented.

Table A3.3. Summary statistics of predicted and observed soil property values (macroporosity and total C) at the validation points of both plots.

			Statistic				
Soil Property†	**Technique§**	**Plot‡**	**Mean**	**Median**	**Variance**	**Min**	**Max**
MP (%)*	OBS	Pre	3.69	3.41	1.42	1.62	6.72
		Post	2.87	2.84	1.55	0.00	5.95
	CB1	Pre	3.28	3.84	0.41	2.56	3.84
		Post	2.90	2.98	0.03	2.52	2.98
	CB2	Pre	3.25	3.68	0.19	2.80	3.68
		Post	2.83	2.90	0.02	2.54	2.90
	CB3	Pre	3.26	3.52	0.43	2.55	4.09
		Post	2.89	2.81	0.09	2.41	3.43
	CB4	Pre	3.25	3.55	0.23	2.66	3.81
		Post	2.89	2.92	0.09	2.45	3.24
	MLR	Pre	3.30	3.44	0.52	0.84	4.71
		Post	-	-	-	-	-
	RK	Pre	3.31	3.40	0.69	0.77	5.43
		Post	-	-	-	-	-
	OK	Pre	3.27	3.27	0.42	1.96	4.82
		Post	2.91	2.94	0.19	2.02	3.66
	REF	Pre	3.23	3.23	0.00	3.23	3.23
		Post	2.81	2.81	0.00	2.81	2.81
TC (%)	OBS	Pre	3.61	3.51	0.90	1.66	5.92
		Post	5.08	4.77	4.09	2.10	16.19
	CB1	Pre	3.60	3.75	0.03	3.41	3.75
		Post	4.92	4.98	0.02	4.64	4.98
	CB2	Pre	3.60	3.79	0.04	3.39	3.79
		Post	4.87	4.95	0.03	4.53	4.95
	CB3	Pre	3.58	3.66	0.10	3.10	3.92
		Post	4.93	4.98	0.04	4.43	5.20
	CB4	Pre	3.59	3.64	0.05	3.32	3.93
		Post	4.92	4.56	0.25	4.53	5.63
	MLR	Pre	3.59	3.62	0.12	2.97	4.20
		Post	4.93	4.75	0.55	3.92	6.53
	RK	Pre	3.57	3.52	0.24	2.43	4.69
		Post	4.84	4.66	0.83	3.29	7.47
	OK	Pre	3.56	3.50	0.26	2.48	4.87
		Post	4.78	4.63	0.43	3.42	7.00
	REF	Pre	3.59	3.59	0.00	3.59	3.59
		Post	4.87	4.87	0.00	4.87	4.87

† MP = macroporosity, TC = total carbon. ‡ Pre = pre-harvested, Post = post-harvested. § OBS = observed mean, CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique. * Summary statistics of transformed data presented.

Graphs plotting ME against RMSE

An assessment of prediction performance can be made by considering root-mean-square error (RMSE) in association with mean error (ME). Such an assessment was not included in Chapter 6 because a more robust assessment based on an analysis of ranks was used instead. However, graphs plotting ME against RMSE for each soil property in each plot are given here. ME is a measure of prediction bias whereas RMSE is a measure of prediction accuracy. The technique with the lowest RMSE is the most precise and the technique with the ME closest to zero is the most unbiased.

Topsoil pH

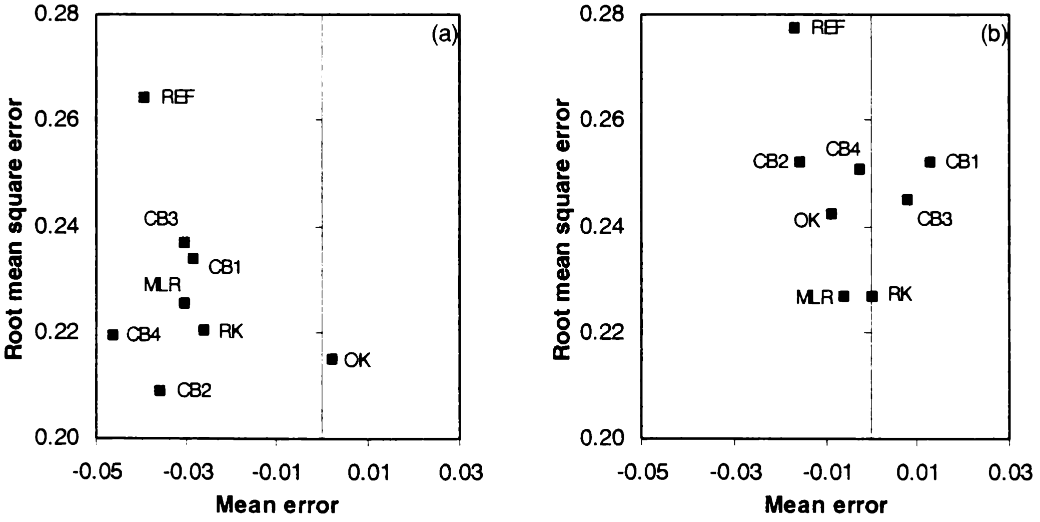

Figure A4.1. Mean error and root-mean-square error of prediction techniques when predicting topsoil pH in (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Available Mg

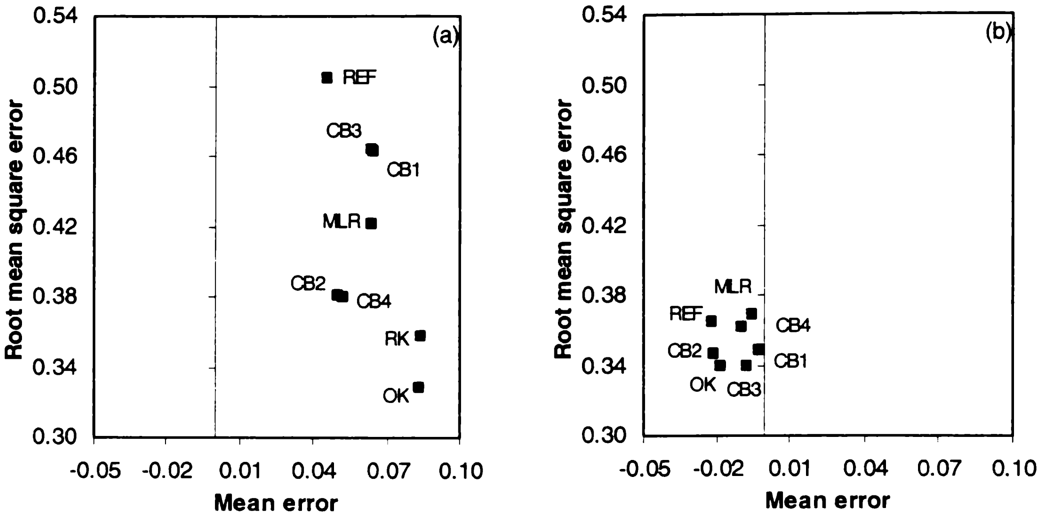

Figure A4.2. Mean error and root-mean-square error of prediction techniques when predicting available Mg in (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Available P

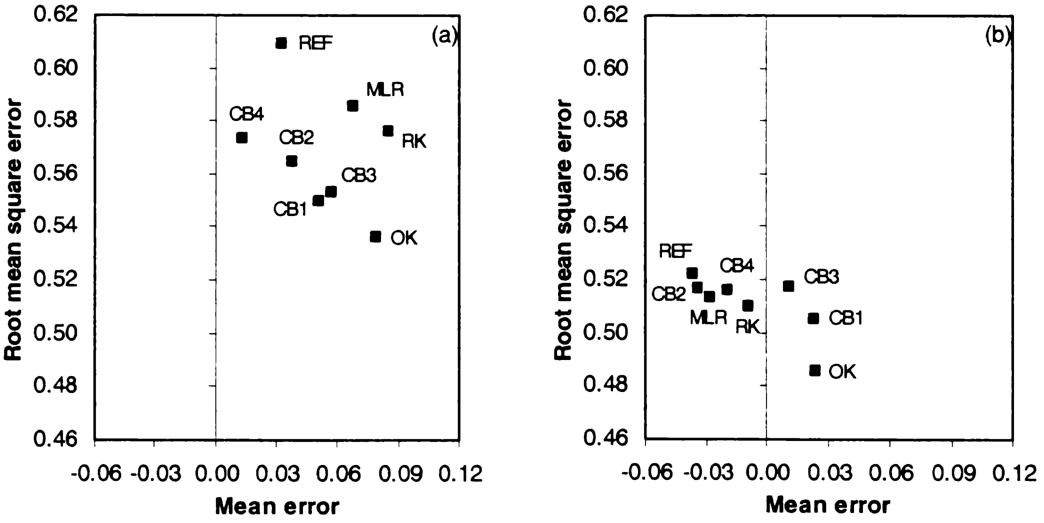

Figure A4.3. Mean error and root-mean-square error of prediction techniques when predicting available P in (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Available K

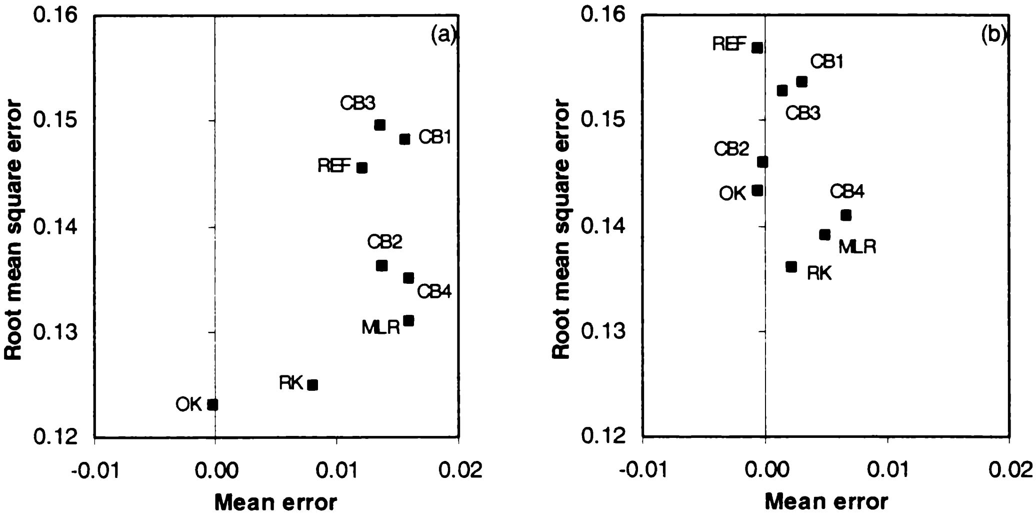

Figure A4.4. Mean error and root-mean-square error of prediction techniques when predicting available K in (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Macroporosity

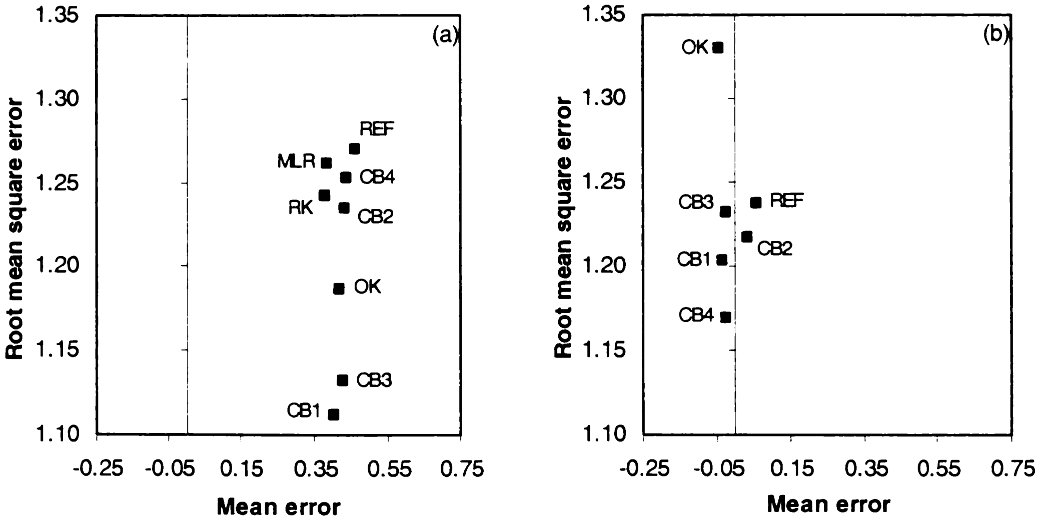

Figure A4.5. Mean error and root-mean-square error of prediction techniques when predicting macroporosity in (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.

Total C

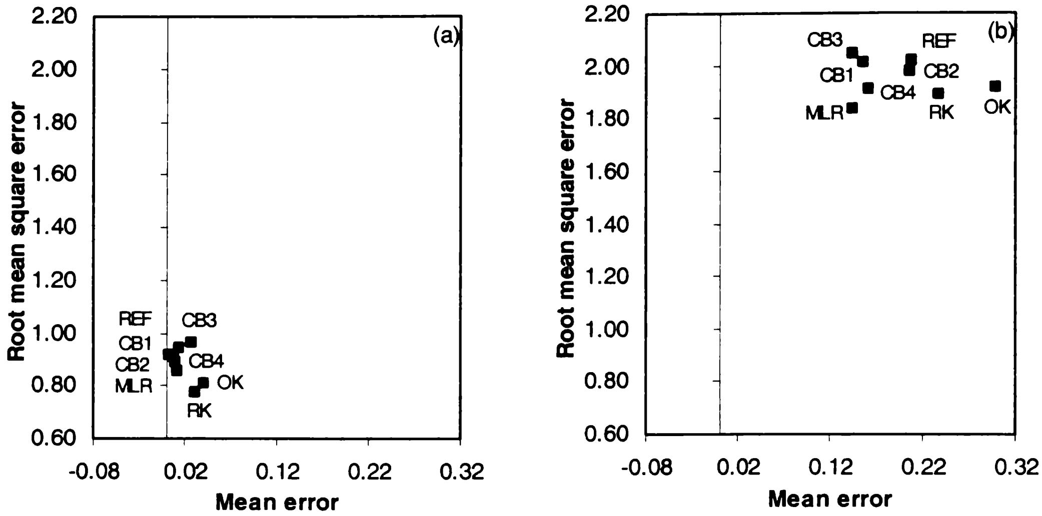

Figure A4.6. Mean error and root-mean-square error of prediction techniques when predicting total C in (a) pre-harvested and (b) post-harvested plots. CB1 = class-based technique 1, CB2 = class-based technique 2, CB3 = class-based technique 3, CB4 = class-based technique 4, MLR = multi-linear regression, RK = regression kriging, OK = ordinary kriging, REF = reference technique.