The influence of soil properties on the vegetation dynamics of Hluhluwe iMfolozi Park, KwaZulu-Natal

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Declaration

I hereby certify that the research reported in this thesis is the result of my own investigation, except as acknowledged herein, and that it has not been submitted for a degree at any other university.

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Abstract

The physical and chemical properties of soils can greatly influence the vegetation patterns in a landscape. This is especially so through the effect that particular characteristics of soils have on the water balance and nutrient cycling in savanna ecosystems. Areas in the savanna environment found in Hluhluwe iMfolozi Park have experienced a number of changes in the vegetation patterns observed. This study, therefore, looks at the effect that soil characteristics may have on the vegetation growth in this area and on the changes that have taken place over time.

Fixed-point photographs, taken every four years, were used to choose fourteen sites in the Park, which showed either a 'change' or 'no-change' in vegetation from 1974 to 1997. The sites consisted of four which had 'no-change' in vegetation, two sites with a slight increase (5-20%) in tree density, three sites with a greater increase in tree density (>20%), two sites with a slight decrease in tree density (5-20%), and three sites with a greater decrease in tree density (>20%). Transects were then carried out at each site, in which the soil was classified to the form and family level. Each horizon was then sampled and the field texture, structure, Munsell colour and depth of each horizon and profile recorded. The data recorded in the field were statistically analysed through a principal component analysis (PCA). The type of horizon, horizon boundary, structure type, colour group and depth for the top and subsoil were included in the models and were analysed with the number given to each site for each of the three sections of the Park, namely Hluhluwe, the Corridor and iMfolozi.

The most prominent textures at all sites were sandy loam, loam, clay loam and silt loam for both the top and subsoil for all site categories. The texture classes were also compared across the Hluhluwe, Corridor and iMfolozi sections. The dominant textures in the Hluhluwe and Corridor sections are loam, clay loam and silt loam for both top and subsoils. Sites sampled in the iMfolozi section appear to have textures mainly associated with the clay loam and sandy loam classes. The structure classes of the soil including sub-angular blocky, granular and crumb which are associated with a moderate structure appear to be the most dominant type in all categories for the topsoil; single-grain and sub-angular blocky classes the main types for the subsoil. Generally the colour of the soil at all the sites sampled was yellower than 2.5YR and the values and chromas mostly fell within the range of 3-5 and 2-6, respectively.

This is also shown in the PCA results obtained, which associate particular soil characteristics with the various sites sampled for the different vegetation change categories investigated.

The samples collected were also analysed in the laboratory after being air-dried. The laboratory analysis included measurements of pH, exchangeable acidity, organic carbon, extractable phosphorus, particle size distribution and cation exchange capacity (CEC). The data recorded in the laboratory were also analysed by PCA. This was used to determine which soil properties are associated with the particular sites investigated.

The pH of the soil, in all areas, fell within a wide range. The pH is influenced by the rainfall in the area and thus sites sampled in the Hluhluwe section are more acidic than those sampled in the Corridor and iMfolozi sections. The topsoils had a higher pH for all the samples and were in the range between 5 and 7. The exchangeable acidity measurements were low, although they were higher in the subsoil as opposed to the topsoil.

The nutrient contents did not appear to vary greatly between the different sites in the Park. Generally extractable phosphorus, CEC and organic carbon were low across the Park. The particle size analysis showed that the clay percentage increases between the top and subsoil for all the sites sampled. The silt and various fractions of sand percentages vary across all sites and are lower than the clay percentage at all sites except the A horizon of the 'slight increase' sites. The 'no-change', and 'increase' sites have a higher percentage of clay as compared to the silt and sand fraction for both the A and B horizon. The 'slight increase' sites have a higher percentage of sand in the A and B horizon, the 'slight decrease' sites have a more equal percentage between the sand, silt and clay fractions in the A horizon and a greater percentage of clay in the B horizon. The 'decrease' sites have a greater percentage of clay and silt in the A and B horizon.

While certain soil properties have a definite effect on the plant growth, no relationship between specific soil properties and vegetation changes was shown. However, it is likely that the soil structure and texture affect the vegetation patterns, through their influences on the water and nutrient holding capacity. With an increase in the clay percentage and more strongly structured soils, plants can access more water and nutrients and this will increase the tree density in an area. However, the recent changes in the vegetation patterns observed in the Park appear to be more associated with other environmental factors. The soil properties analysed would have generally been more constant at the sites sampled, particularly over the relatively short period of time in this study. Therefore, the changes which were recorded in the fixed-point photographs would have been enhanced by other factors experienced in the Park, including fire and the effect that grazers and browsers have on the vegetation.

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Introduction

Plant communities in savanna ecosystems exhibit widespread and rapid changes in response to variations in different environmental factors. Therefore, in order to better understand and manage these ecosystems it is important to study the relationship that exists between vegetation growth patterns and these environmental features. Among the different environmental aspects, soil plays a large role in influencing vegetation growth and can control the presence or absence of plants in these areas (Breshears and Barnes, 1999; Jafari *et al*., 2004).

Most sites within a savanna ecosystem will lie within a continuum, the extremes of which are open grassland and forest. The position of an area within this grassland/forest continuum and thus the relative proportions of grassland and woody cover affect many properties, including the water balance, erosion rates and nutrient cycling. Therefore, the ability to predict changes in landscapes that are dominated by a mixture of woody and herbaceous vegetation is one of the top priorities for global change research (Belsky and Canham, 1994; Davenport *et al*., 1998). A potentially important organizing principle in savanna systems is the various characteristics of the soils, including the nutrient status and soil-water system which is influenced by the texture. Soil properties, which are interrelated, can also affect the carbon and nutrient cycling, through interactions between the physical, chemical and biological soil processes (Hook and Burke, 2000).

Areas in the savanna environment found in Hluhluwe iMfolozi Park have experienced a number of changes in the vegetation patterns observed. Therefore a study of the factors which have influenced these changes can aid in understanding the relationship between properties which affect savanna ecosystems. A number of studies on environmental aspects, such as the fire management and grazer and browser influences on the vegetation patterns in the Park have been carried out. However, there is limited knowledge on the effect that the varied soil types have on the vegetation dynamics and how these have changed. There are a number of international studies on the influence of soil properties, such as texture and the fertility status, on the balance between woody and herbaceous vegetation. However, there is little information on South African soil properties and their influences on the savanna ecosystems. This is particularly so in KwaZulu-Natal.

Through the use of a visual record kept on the vegetation of Hluhluwe iMfolozi Park, this study aimed to identify the soil characteristics that have the greatest influence on the vegetation changes which have occurred in different areas of the Park. Soil sampling was carried out in areas which were categorised as having a ‘change’ or ‘no change’ in the vegetation growth patterns found. Samples which were analysed both physically and chemically were then related to the changes in plant growth which have taken place, through a series of statistical analyses. These examined relationships which exist between specific soil properties and the sites at which either a ‘change’ or ‘no change’ had taken place over the time period. The physical soil properties were generally recorded in the field, while the chemical analyses were conducted as a laboratory investigation. The results of this study can be used to further understand the various interrelated environmental factors which have an effect on vegetation growth in Hluhluwe iMfolozi Park.

Chapter One gives a review of some of the literature available, which presents an insight into how different soil properties affect vegetation growth in the savanna ecosystem. Chapter Two gives a description of the study area and the various environmental factors which play a role in the environment experienced. Chapters Three and Four explain how the study was completed and the results found and Chapter Five summarises all the information and draws general conclusions.

Chapter One

Soil properties and vegetation growth in savanna ecosystems

1.1. Introduction

Plant growth patterns are governed by a combination of environmental and historic factors, as well as the local conditions at a particular site (Barbour *et al.*, 1987). Among the environmental factors, the physical and chemical properties of soil can have a great influence on the availability of resources for plant growth and thus are able to encourage or constrain habitation by different plant types. They can therefore have a marked effect on the vegetation patterns of a particular area (Chapin *et al.*, 1993).

The principal influences of soil resources on vegetation growth are via nutrients, aeration and moisture (Ellis and Mellor, 1995). However, there are a number of other factors that can determine how vegetation patterns are created in certain areas. These include both soil chemical factors such as pH and exchangeable acidity, and physical factors such as the depth, consistence, structure and texture. The soil resources required for plant growth are heterogeneously distributed throughout the soil system and this has a significant impact on the ecology of individual plants and plant populations (Wijesinghe *et al.*, 2005).

The availability of soil resources to different plant types can thus be a driving force in ecosystem succession. This is due to the environmental and community factors which determine the vegetation growth patterns, interacting in such a way that the abundance and distribution of plant species is determined by spatial environmental heterogeneity (Law *et al*., 1993; Bullock, 1996). Therefore changes in soil properties across an area can influence changes in the types of vegetation patterns found (Chapin *et al*., 1993; Koerselman and Meuleman, 1996).

1.2. Soils influence on vegetation growth

1.2.1. Nutrient supply and availability

The availability and supply of nutrients from the soil can be two of the most important factors affecting the number of species and diversity of vegetation in a particular area (Grime, 1979;

Roem and Berendse 2000). Nutrients can act as determinants of the composition, structure and productivity of vegetation (Smit, 2005). Tilman (1988) suggests that theory predicts that the best competitor for a single limiting resource, for example N, should displace all other species from a habitat independent of their initial densities. This, as shown by Chapin *et al*. (1993), is due to the rates of nutrient cycling correlating closely with the availability of most soil resources, and that in turn leads to changes in the types of species in an area.

Hayati and Proctor (1990) have shown that the availability and cycling of the major nutrients such as N, P and K can cause a shift in the dominance of certain species due to the availability of these nutrients being dependant on certain chemical cycles. This could lead to a change in the balance between woody and herbaceous vegetation (Kirkham *et al*., 1996; Critchley *et al*., 2002). An example of this can be seen in Kirkham *et al*. (1996) where it is seen that a high concentration of plant – available N or P recorded in soils influences changes in individual species abundance.

Depending on their chemicals specific composition some nutrients are not available to plants at all times. Therefore, while nutrient content may be critical in determining the fertility of a soil and thus its effect on vegetation types, nutrient availability can be equally important, as the supply of nutrients does not necessarily mean that they will be taken up by the plant (Hayati and Proctor, 1990). The loss of various nutrients via leaching also greatly affects the fertility status of a soil. Soil fertility is thus related to the combined effect of soil texture and the plant available moisture (Walker and Langridge, 1997). Nutrient availability is also affected by the quantity held in exchangeable form on clay and organic colloids. This is dependent on the soil texture with sandier soils having been shown to be less fertile as compared to clay soils, due to both a direct effect of loss of clay and the often low organic matter content of coarse-textured soils (Dodd *et al*., 2002).

The spatial and temporal heterogeneity of nutrients in natural soil environments commonly have significant effects on habitat quality for different vegetation types. Due to this heterogeneous nature of natural environments, different vegetation types benefit diversely from the conditions created in soil environments (Aerts, 1999; Wijesinghe and Hutchings, 1999; Hutchings *et al*., 2003; Hutchings and John, 2004).

An increase in nutrient availability is known to reduce species richness as the more competitive and fast growing species will be favoured and thus will replace slower growing vegetation (Grime, 1997). Species richness can also be greater at sites where plant growth may be limited by different nutrients. Competing plant species that are limited by different nutrients may coexist because they use different resources, or if each species is competitively superior with respect to the nutrient that limits its growth (Braakhekke, 1980). However, the type of nutrient limitation may not only affect the number of species but also the species composition of an area. For example, communities where plant growth is limited by N differ in species composition from plant communities that are limited by P (Verhoeven *et al.*, 1996). The vegetation growth in an area is therefore a factor of both the type and quantity of nutrients found within the soil and also the soil properties which either inhibit or increase the availability of these to plant roots.

1.2.2. Soil water and aeration

Plant available water can be the single most important factor governing the structure and function of savannas (Walker and Langridge, 1997), due to the seasonal nature of soil water in each of the horizons. With the herbaceous layer in a savanna shown to be the competitor for water in the topsoil (Knoop and Walker, 1985), a low rainfall year would lead to a reduction in the drainage of water into the lower horizons. This would be due to the rapid uptake of topsoil water by the herbaceous layer thus affecting tree growth and the structure of the savanna ecosystem (Walker and Langridge, 1997). Savanna plants can, however, remain active across a wide range of soil water potentials from field capacity down to just above the wilting point (Gunn, 1974; Obrist *et al*., 2004; Wu and Archer, 2004).

Soil texture and structure have been shown to have the greatest influence on the soil water and aeration and thus play an important role in controlling vegetation structure (Dodd *et al*., 2002). This is due to air and water in the soil profile having a reciprocal arrangement in terms of their occupancy of soil pore space and thus are determined by the soil texture (Ellis and Mellor, 1995). The soil texture determines to a large extent the drainage conditions and pore size and thus the tenacity with which water is held by soil colloids (Brady, 1984; Epstein *et al*., 1997).

The balance between the amount of soil water and air in the profile in savanna ecosystems depends on the percentage of each individual size fraction of soil particles. Lane *et al*. (1998) show that in semi-arid regions coarse-textured soils may lose less water through evaporation than fine textured soils and thus may have a higher water availability. The drainage of water into the deeper horizons can also increase the quantity of water in coarse-textured soils (Tsoar, 1990).

Plants, however, vary in their abilities to extract water from the soil and this leads to the creation of vegetation patterns in areas. Other important soil properties, including swelling and shrinkage, consistency, plasticity and ease of compaction, are also affected by the amount of water in a soil and they thus have an effect on vegetation growth (Hassett and Banwart, 1992). Therefore soils differ with respect to the amount of water they can store and make available to vegetation depending on the type of clay present and the different pore sizes. In order for a soil to support vegetation growth and allow the functioning of plant roots, a balance must exist between pores which store water and those which are free for the movement of essential gases (Wild, 1993). Vegetation growth is generally negatively affected by poor aeration through the decrease in respiration affecting root growth and the absorption of nutrients (Hutchings *et al*., 2003).

Soils have their own microclimate and can thus influence the respiration of vegetation and the decomposition of organic residues by microorganisms. A study conducted by Hook and Burke (2000) found that soil aeration affects the soil organic matter quantity and quality. Anaerobic decomposition of organic materials is much slower than under aerobic conditions and the end products of decomposition are also different, with methane often being produced. If the decomposition yields are also less complete, other products such as organic acids are produced and these may accumulate in toxic quantities. The soil water and aeration balance that exists in savanna ecosystems is thus important in terms of its influence on nutrient availability and organic matter decomposition.

1.3. Soils and vegetation growth patterns

1.3.1. Physical controls

The physical properties of soils including texture, structure, consistency, density, porosity and depth of individual horizons are dominant factors affecting vegetation growth patterns in a particular area (Donahue *et al*., 1977). These soil properties influence the availability of oxygen in the soil and the mobility of water into and through the soil profile (Hook and Burke, 2000). According to Jafari *et al*. (2004) and Wu and Archer (2004), soil physical properties can therefore affect vegetation growth patterns as they influence the distribution and density of woody plant species in savanna ecosystems. Changes in woody plant abundance can also be locally mediated by factors such as soil texture and depth.

A number of models (Walter, 1971; Walker *et al*., 1981; Sala *et al*., 1997) have suggested that grasses or herbaceous vegetation are the superior competitors for soil water in the topsoil while woody species have a greater access to water in the subsoil or lower horizons. These assumptions can therefore be used to suggest that woody vegetation will dominate on coarse-textured soils, as these allow deep percolation of soil water and thus deep-rooted species will become competitive (Walker and Noy-Meir, 1982; Knoop and Walker, 1985). However, other studies have documented that woody species differ with respect to the depths from which they extract water from the soil (Pelez *et al*., 1994; Montana *et al*, 1995; Breshears *et al*., 1998). Various shrub species have a shallower distribution of roots as compared to tree species and several semi-arid plant communities include woody species that are able to extract soil moisture from shallow depths and thus are likely to compete with grasses or herbaceous plants (Miller and Gardiner, 1998). It can thus be seen that while soil texture is an important factor influencing patterns of vegetation structure through its relationship with soil water availability, there are differences between woody plant species with respect to where they obtain water, and there is also heterogeneity of soil water within the soil profile. The vegetation structure is therefore dependent on the soil characteristics and the species present within a particular area (Breshears and Barnes, 1999).

Soil texture can also greatly affect the amount of soil organic matter and its accumulation, as well as influence the variation in soil organic matter quality (Hook and Burke, 2000). This is due to daily and seasonal changes in the soil water and temperature regimes that are important controls of carbon and nitrogen mineralisation, especially in semi-arid regions. The microclimate within the soil, which is affected by the physical properties such as texture, also interacts with the distribution and quality of the soil organic matter and thus determines the carbon and nitrogen turnover and availability (Burke, 1989). Therefore soil texture may influence the distribution of soil carbon and nitrogen across a landscape either in association with topography or independently (Hook and Burke, 2000).

Soil depth and stability are also important contributors to the amount of soil water available for plant growth. Shallow soils can limit vegetation growth due to restricted root penetration or instability of the ground. However, shallow soils do not always limit root depth as in some cases roots can penetrate into the underlying bedrock (Chapin *et al*., 1987).

1.3.2. Soil pH

While the soil physical environment can impose various constraints on the composition and structure of plant communities (Burgman, 1987), the soil chemical factors can exert an influence on vegetation structure and can also act as additional influences in their own right (Ellis and Mellor, 1995). The soil chemical factors mainly relate to soil pH and the reaction of the soil solution. Due to the fact that vegetation responds markedly to its chemical environment, the soil reaction and the factors associated with it, can affect the vegetation patterns of certain areas (Brady, 1984; Beegle and Lingenfelter, 1995).

Studies, which have looked at soil pH and its affect on plant growth, are generally limited to crop plants and do not include natural vegetation. However, du Pisani *et al*. (1986) reported that the soil pH does play a role in the growth of herbaceous vegetation, particularly grass species. While most species can tolerate a wide range of pH values, soil acidity adversely affects the growth of vegetation through its influence on the solubility of minerals and nutrients. This can also lead to a negative effect on the chemical composition of the above-ground plant mass.

The effect of pH on nutrient availability has been studied in greater detail and reports show that various nutrients become less or more available at different pH values (Abule *et al*., 2004;

Hagos and Smit, 2005). Iron, manganese, and zinc are less readily available in alkaline conditions and at very low pH values these nutrients can become soluble and toxic to plants. At high pH values bicarbonate ions can occur in concentrations which reduce nutrient uptake. Carbonates in the soil can also accumulate as precipitates around the roots of plants and this inhibits water and nutrient uptake (Hassett and Banwart, 1992).

An increase in woody plants in an area can also influence the soil pH through the roots, particularly so with regard to root exudates which have been shown to both increase and decrease the pH (Bagayoko *et al*., 2000). However, the stabilization of soil pH through buffering is an effective guard against these changes. The buffering of soils is a distinct resistance to a change in the pH of the soil matrix due to an equilibrium between the exchange acidity and the hydrogen ion concentration of the soil being reached and a resistance to change in pH values established (Brady, 1984).

1.4. Other environmental factors and vegetation growth patterns

Trees and grasses interact by many mechanisms, some negative including competition and some positive such as through facilitation. The strength and type of interaction vary in both time and space and this allows a great array of possible outcomes. This spatial pattern of grasses and woody plants, especially in savanna ecosystems, are dictated by complex and dynamic interactions among climate, topography, soils, geomorphology, herbivory and fire. These interactions may be interrelated or opposed and may create variation or positive feedbacks. In many areas, however, a large number of natural factors interact in such a way that it is difficult to identify and quantify the key elements of a particular ecological structure (Scholes and Archer, 1997). A few of the ecological processes that regulate the balance between woody and herbaceous vegetation are reviewed below.

1.4.1. Environmental heterogeneity

Vegetation requires a balance of resources including energy, water and mineral nutrients to maintain optimal growth. Natural environments, however, differ in their ability to provide these resources and this heterogeneity leads to diverse vegetation patterns (Chapin *et al*., 1987). Plants are strongly affected by heterogeneous resource distribution even if the total resource supply remains constant, and this response to heterogeneity can differ between species, the developmental stage of the plant and on the type of heterogeneity experienced (Hutchings and John, 2004).

Soil-based resources are heterogeneously distributed at a variety of scales in time and space. The pattern of acquiring these resources, especially nutrients, can significantly affect the performance of individual plants and plant populations, as response to this spatial pattern of nutrient delivery is both species and pattern specific (Wijesinghe *et al*., 2005). This is due to species differing in their ability to select patches of nutrient-richness and in the speed with which they can take up the available nutrients. This heterogeneity in resource supply can thus alter competitive hierarchies among plant species and increase the intensity of competition experienced by plants (Einsmann *et al*., 1999).

The heterogeneous nutrient availability of an area affects the species composition of plant communities. Plants sharing a resource supply and thus competing with one another for nutrients will devote a higher proportion of their biomass to roots than non-competing plant individuals and communities. If the nutrients are heterogeneously distributed then this effect will be intensified because the nutrients occupy a smaller volume of the substrate (Fransen *et al*., 2001). Plant species also differ in their ability to obtain the unevenly distributed nutrients. Therefore some species will be at a disadvantage if their root systems are at a distance from a nutrient source or other resource. This is especially so in a community where many plants are competing for resources (Fitter, 1982).

The impact that environmental heterogeneity can have on community structure can also affect the ability of newly arriving species to colonize the community. This could be due to variation in the overall biomass and overall intensity of competition within the community, or because some parts of the habitat support less biomass than others. Species differ in the extent to which their roots explore the substrate and this could be reflected in differences in community structure (Davis *et al*., 2000). Thus vegetation with extensive and rapid root growth, including woody plant species, should be at an advantage in situations where the supply of resources is spatially unpredictable (Crick and Grime, 1987).

Heterogeneity can, however, also be positive for vegetation growth. This can be seen when plants respond to the scale of heterogeneity through the scale of their root system and the scale of patches of resources. Smaller root systems will be more closely matched to uniformly-poor availability of resources and this will confer a competitive advantage for these plants at one scale of heterogeneity. Other scales, however, can be detrimental to certain species as the plants try to achieve the optimal distribution of roots for the scale of the patches of resources. Therefore not only the presence of heterogeneity, but also its precise form can be expected to influence the relative success of individual species and thus vegetation communities as a whole (Wijesinghe and Hutchings, 1997).

1.4.2 Fire

The fire management of an area can induce changes in the vegetation community structure, the biomass production and the litter accumulation. This is due to changes in species abundance through disturbances, alterations in the canopy structure and form, and the formation of gaps in vegetation. However, fire also increases the soil nutrient availability through the decomposition of organic material. The effects of fire on vegetation generally varies at different levels of species richness, especially if it induces changes in the canopy structure and the soil nutrient availability (Jafari *et al*., 2003). According to Dimitrakopoulos *et al.* (2006) community resistance to fire increases significantly with increasing species richness. However, another study by Pfister and Schmid (2002) found that a species-poor ecosystem was more resistant than a species-rich one. It is thus the type of species present and their response to the disturbance caused by fire that makes a community resistant.

The impact that fire can have on vegetation patterns can also vary due to the seasonality, the fire intensity and the frequency of burning. While frequent burning will decrease the probability of new stems growing through to larger size-classes, and therefore give a competitive edge to grass growth, it is dependent on the rate of the fuel-load accumulation and this in turn is dependent on the rainfall of the area and the intensity of grazing (Shackelton and Scholes, 2000). The fire frequency will affect the woody species in a community. As shown in a study by Shackelton and Scholes (2000) the biomass, density, height and basal area of woody species decreased with an increase in fire frequency. This can be a factor in allowing grasses and trees to coexist in certain environments. Areas that were protected from fire have been shown to have an increase in woody plant cover. However, reports by Strang (1974) and Trollope (1982) found that fire frequency did not have a great effect on the density of plants over a long period. The season in which a fire burns also has effects on vegetation through its influence on the fire intensity. It is thus clear that while fire does have an impact on the vegetation growth patterns of an area, the lasting long term effects on the community structure depends not only on the fire intensity and frequency, but also on the species composition and the ability of the plant community to be resistant to the disturbances created.

1.4.3 Climate

Climatic conditions, including rainfall, seasonal water balance, the length of the growing season and winter temperatures can strongly influence plant and animal species (Prentice *et al*., 1992). This relationship between geographic patterns of vegetation and climate is one of the oldest observations in plant ecology and has led to the creation of several global classification schemes or biomes. Depending on the biome or ecosystem there are various environmental limits that lead to the creation of different vegetation patterns (Emanuel *et al*., 1985). In the savanna ecosystem, for example, there is water limitation for at least part of the year and thus competition between woody and herbaceous vegetation will be for plant available moisture in the soil (Amundsan *et al*., 1995). However, in more temperate ecosystems Woodward (1987) suggested that minimum temperatures have a great influence in determining the different types of woody plants found in an area. Recent climate change as a result of anthropogenic activities has already resulted in observations of shifting vegetation boundaries on a global and local scale (Flannery, 2005). However, to what extent these resulting shifts will occur is not known.

While it is widely established that climate is a major determinant of vegetation structure and function, ecosystems can also affect the climate, particularly through vegetation cover and soils. This two-way relationship may occur through biophysical processes such as changes in water or energy balance or through biogeochemical processes including changes in the proportion of gases such as carbon dioxide and methane (Foley *et al*., 2003). This, however, occurs on a more global scale, and at the local level the effect that climate has on the moisture availability and the temperature will be one of the greatest determinants of the vegetation patterns of the area (Amundsan *et al*., 1995).

1.4.4 Herbivory

It has been shown by a number of studies that herbivores can change the vegetation patterns of a particular area (Andren and Angelstam, 1993; Pastor *et al*., 1999; Hessl and Graumlich, 2002; Ward and Or, 2005). This may be due to either herbivores affecting tree growth and reproduction or through their grazing of palatable grasses and can have both positive and negative effects on all types of plants found in an area. In addition to consumption of the foliage, herbivores can affect tree growth patterns through trampling and seed predation, and also through soil compaction which reduces the seedling survival rate. Seed predation also results in a reduction in the number of potential trees that can migrate into new environments (Cuevas, 2000). These negative effects are, however, mediated by other positive effects that cause an increase in tree biomass. For example, while trampling by large herbivores may have a negative effect on seedlings, it may also reduce existing vegetation cover and thereby increase soil temperatures and thus facilitate vascular plant growth (Cairns and Moen, 2004).

The effects of herbivores on vegetation patterns are also coupled with the effects of fire. A high grass biomass can affect the biomass of trees by fueling fires. Grazing reduces this fuel load and thus the fire frequency and intensity, thereby allowing tree communities to be more resistant to the effects of fire. Browsing, on the other hand, keeps tree species within the flame zone and conversely fires keep woody plants browsable. Therefore in many areas the patterns of tree-grass mixtures is strongly influenced by a grazer-browser-fire interaction (Scholes and Archer, 1997).

1.4.5 Topography

The topographic features of an area can greatly influence vegetation patterns depending on the extent to which the portions of a landscape may differentially capture or retain scarce water and nutrient resources. Changes in vegetation patterns within the same climate and experiencing similar disturbances vary with hillslope-to-hillslope variation in topography-based hydrologic features. This is especially so in semi-arid regions where there is a strong linkage between vegetation patterns and the slope steepness and length and the associated run-off/run-on relationships (Wu and Archer, 2004).

The catena model, which is used to interpret soil landscapes, assumes that within geologically and climatically similar areas the hydrologic and geomorphic processes generate consistent patterns of soil development, biogeochemistry and ecology along hillslopes. Therefore the differences between the erosional uplands and the depositional lowlands reflect the long-term redistribution of soil materials and the modification of soil water availability. These influence the soil organic matter accumulation and quality and the nutrient cycling and thus the vegetation structure of the area (Hook and Burke, 2000). However, vegetation communities can also have their own influence on landscape water movement and thus the patterns created may be affected by the relationship between these features (Wilcox *et al*., 2003).

1.5 Conclusion

One of the central goals in ecology is to describe and explain patterns of distributions and abundance of species (Cairns and Moen, 2004). While vegetation patterns are influenced by many interrelated factors, the properties of soils play an important role in their ability to affect these different elements and thus the vegetation structure of an area (Ellis and Mellor, 1995). The tree-grass interactions of semi-arid savanna ecosystems include elements of competition and facilitation, which vary in complexity, and in both time and space and this allows the plant communities to be sensitive indicators of variations in the environmental conditions. A local distribution of species will therefore be controlled by changes in soil properties which can either influence other environmental factors such as nutrient and water availability or be influenced by the various elements including the topography (Scholes and Archer, 1997).

Plant communities themselves also modify their habitats through changing certain soil properties depending on differences in their structure and density. This has consequent effects on evapotranspiration, run-off, rainfall interception, shading and organic matter accumulation, which in turn change the vegetation structure (Gunn, 1974). It is thus clear that the occurrence and distribution of vegetation is not only due to the availability of water but that there is also an interaction between disturbances such as fire and herbivory, the landscape and climate, the soil and the vegetation itself.

The vegetation patterns existing in a savanna ecosystem are thus a function of different variables and the interactions that exist between them. Fire, herbivory, climate and topography all have an effect on soil characteristics and thus the different physical and chemical properties of soils are able to affect and change particular vegetation dynamics within an area. The growth of vegetation can also be unique to a particular site and thus the management of these areas needs to take this into consideration. Through studying the various soil properties of sites where vegetation dynamics occur, such as in Hluhluwe iMfolozi Park, the specific soil attributes which affect vegetation growth can be highlighted and the causes of vegetation dynamics better understood. This can aid in the management of areas in order to conserve these sites.

Chapter Two.

Study site: Hluhluwe iMfolozi Park

2.1. Location and general site description

Hluhluwe iMfolozi Park (HIP) is situated in northern KwaZulu-Natal between 28^{o}00’ and 28^{o}26’S and 31^{o}43’ and 32^{o}09’E (Figure 2.1). It is about 300 kilometres from Durban and has an area of 96 453ha. The Park consists of the Hluhluwe section in the north, the iMfolozi section in the south and a Corridor section that links the areas together (Charlton-Perkins, 1995). The landscape is undulating to hilly and there is a gradual drop in altitude from west to east along the Natal Monocline (Van Niekerk, 2002). Hluhluwe iMfolozi Park is comprised of five management areas namely Manzibomvu, Nqumeni, Masinda, Mbhuzane and Makhamisa. The three major rivers in the Park are the Black iMfolozi, the White iMfolozi and the Hluhluwe. The Park was set aside as a reserve in 1895 and is Africa’s oldest protected area. The three sections have been managed as one large protected area since 1980 and the Corridor section, which was state-owned, was incorporated into the Park in 1989 (Lagendijk and Kusters, 2001).

2.2. Climate

The Park is characterised by a mild-subtropical climate. The average annual rainfall recorded at Hilltop Camp in the Hluhluwe section is 1014mm. However, there is a variation in the climatic conditions experienced in the different sections of the Park (Figure 2.2). The rainfall recorded in the iMfolozi section at Mpila camp is 635mm, thus showing that the northern Hluhluwe section receives the majority of the rainfall annually (McKean, 2000). Approximately 72% of the mean annual rainfall occurs from October to March, with an average of over 60mm per month in this time. While most rainfall is received in the summer months there is considerable variation from one year to the next (Kruger, 1996). The mean monthly temperatures range from 23^{o}C to 27^{o}C in summer, and from 19^{o}C to 22^{o}C in winter (Charlton-Perkins, 1995).

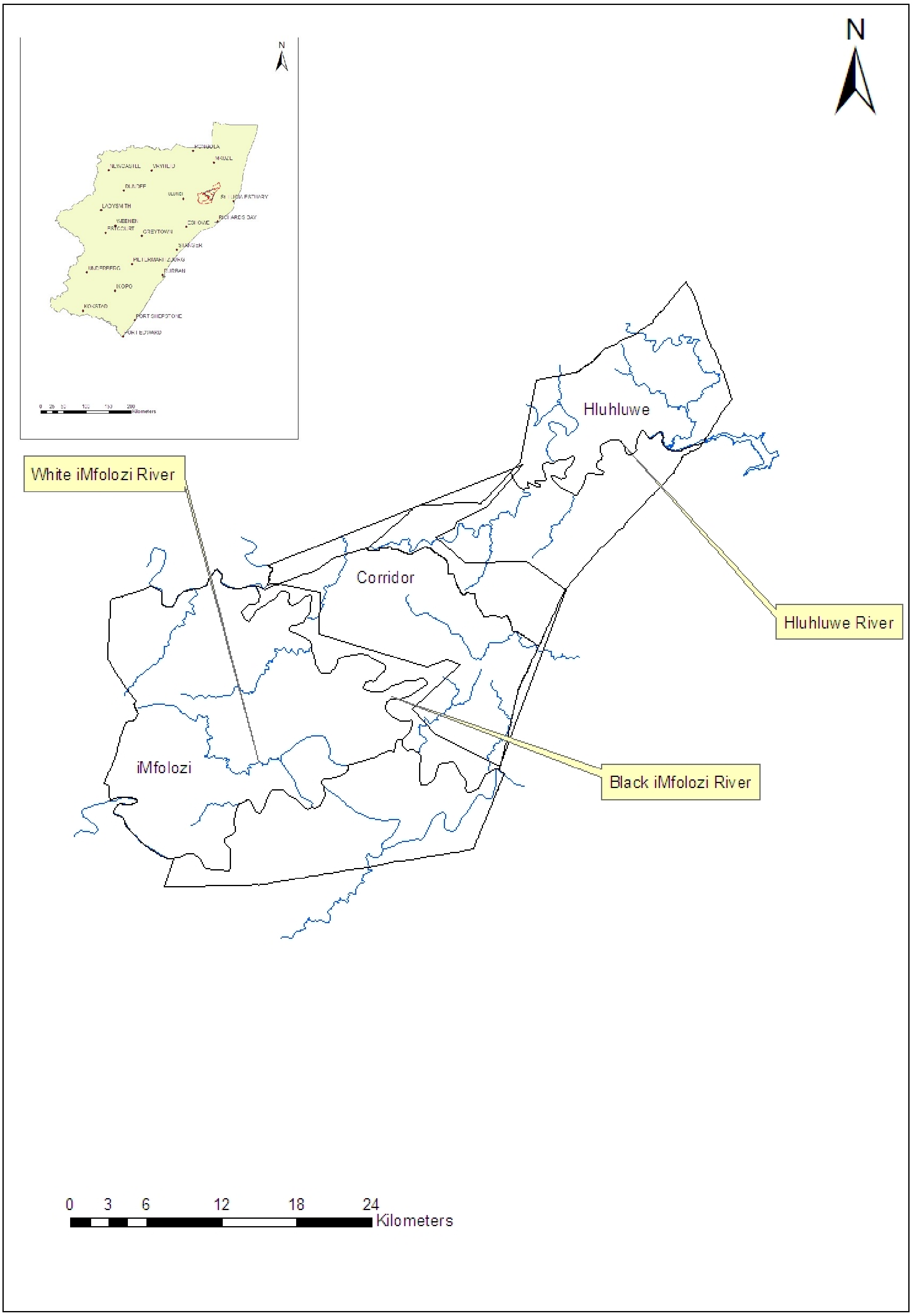


Figure 2.1. Hluhluwe iMfolozi Park, with the main rivers of the area shown

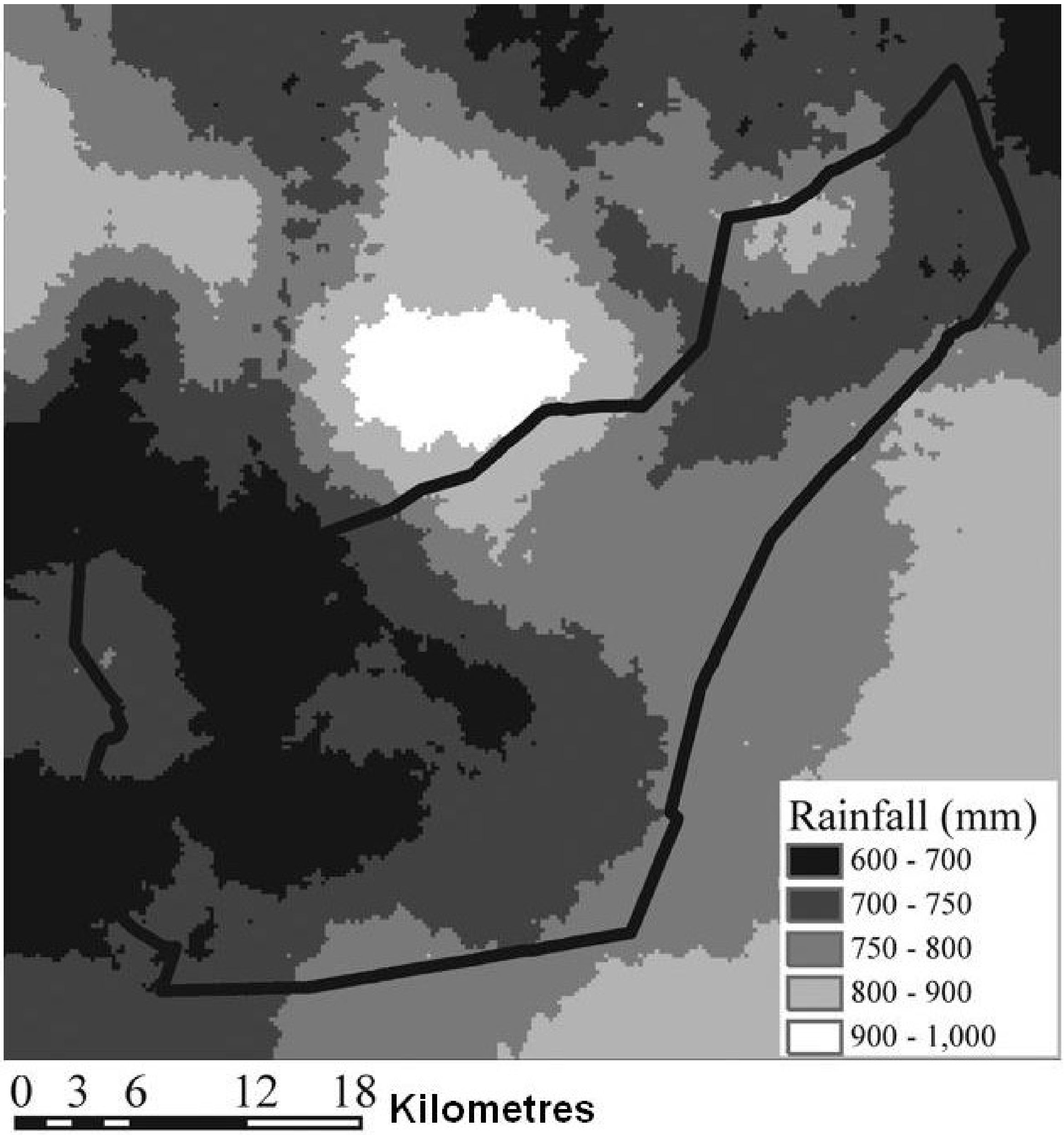


Figure 2.2. Mean annual rainfall range in Hluhluwe iMfolozi Park (from Schulze, 1997)

2.3. Infrastructure

The infrastructure of HIP generally consists of the tourist and management roads and camps. The two main accommodation areas are the Hilltop and Mpila camps, which are found in Hluhluwe and iMfolozi, respectively. Other accommodation areas include the ‘bush camps’, which are situated around the park in all the three main sections, Hluhluwe, the Corridor and iMfolozi. Artificial water points, hides and picnic spots also make up the general infrastructure, and are found throughout the Park, as well as the tourist site, game capture and conference centre (the Centenary Centre), found in the iMfolozi section.

2.4. Fauna

Hluhluwe iMfolozi Park supports a wide variety of fauna and thus has a great diversity of grazers and browsers and large and small predators (Kruger *et al*., 1999). There is no large migration into or out of the Park. The grazer density is estimated at 90 kg/ha from species including impala (*Aepyceros melampus*), nyala (*Tragelaphus angasii*), buffalo (*Syncerus caffer*), wildebeest (*Connochaetes taurinus*) and white rhino (*Ceratotherium simum*) (Archibald and Bond, 2004). The browser and mixed-feeder populations, which play a role in influencing the tree patterns of the area include species such as giraffe (*Giraffa camelopardalis*), nyala (*Tragelaphus angasii*), black rhino (*Diceros bicornis*) and elephant (*Loxodonta africana*). The carnivores include wild dog (*Lycaon pictus*), lion (*Panthera leo*), leopard (*Panthera pardus*) and cheetah (*Acinonyx jubatus*) (Kruger *et al*., 1999).

2.5. Vegetation

Hluhluwe iMfolozi Park lies within the Zululand Thornveld subcategory of coastal tropical forest types and the Lowveld subcategory of tropical bush and savanna types (Acocks, 1988). The Zululand Thornveld occurs within the rainfall range experienced by HIP, especially within the Hluhluwe section. The Lowveld vegetation, which occurs in the rainfall range of 500-750mm annually, is more common in the iMfolozi section. There are five basic vegetation groups and each is characterised by various dominant plant communities. The forests are found in the northern Hluhluwe section on the hillsides, which receive the greatest amount of rainfall or as riverine belts. Woodland communities are found in various bottomland areas or on rocky hillslopes and the open woodlands are more common in the iMfolozi section. The thickets or savanna cover more than half of HIP (Kruger, 1996), and much of the grassland areas are composed of tall bunch-grass communities (Archibald and Bond, 2002).

The vegetation structure in various areas of the Park has, however, changed notably. The dominant plant classes have either increased the area in which they are commonly found, or have been reduced significantly (Figure 2.3). The forest area has increased greatly in the northern tip of the Hluhluwe section. The thicket and woodland communities have also extended into many areas of the park, especially within the southern iMfolozi section. The open woodland, however, appears to have decreased significantly between 1975 and 1996 and these areas have probably been encroached by thicket vegetation species. The grassland, on the other hand, has increased throughout the Park, particularly within the more southern areas.

Although the classification of the dominant vegetation classes are indiscriminate the changes appear to be consistent with the fact that bush encroachment throughout the reserve is creating a general trend towards a closed woodland and forest vegetation (Van Niekerk, 2002). This general trend can also be seen when comparing the more detailed maps by Whately and Porter in 1975 and Dora in 2001. The thickets shown on the 1975 map (Figure 2.4) appear to have encroached into many areas of the park, especially into the southern parts, and are classified as dense and medium thicket in the 2001 Dora map (Figure 2.5). The grasslands of 1975 also appear to have been reduced on the 2001 map. This is probably due to communities of tree species that encroach into grazing lawns being much more widespread in 2001 (Balfour and Howison, 2001).

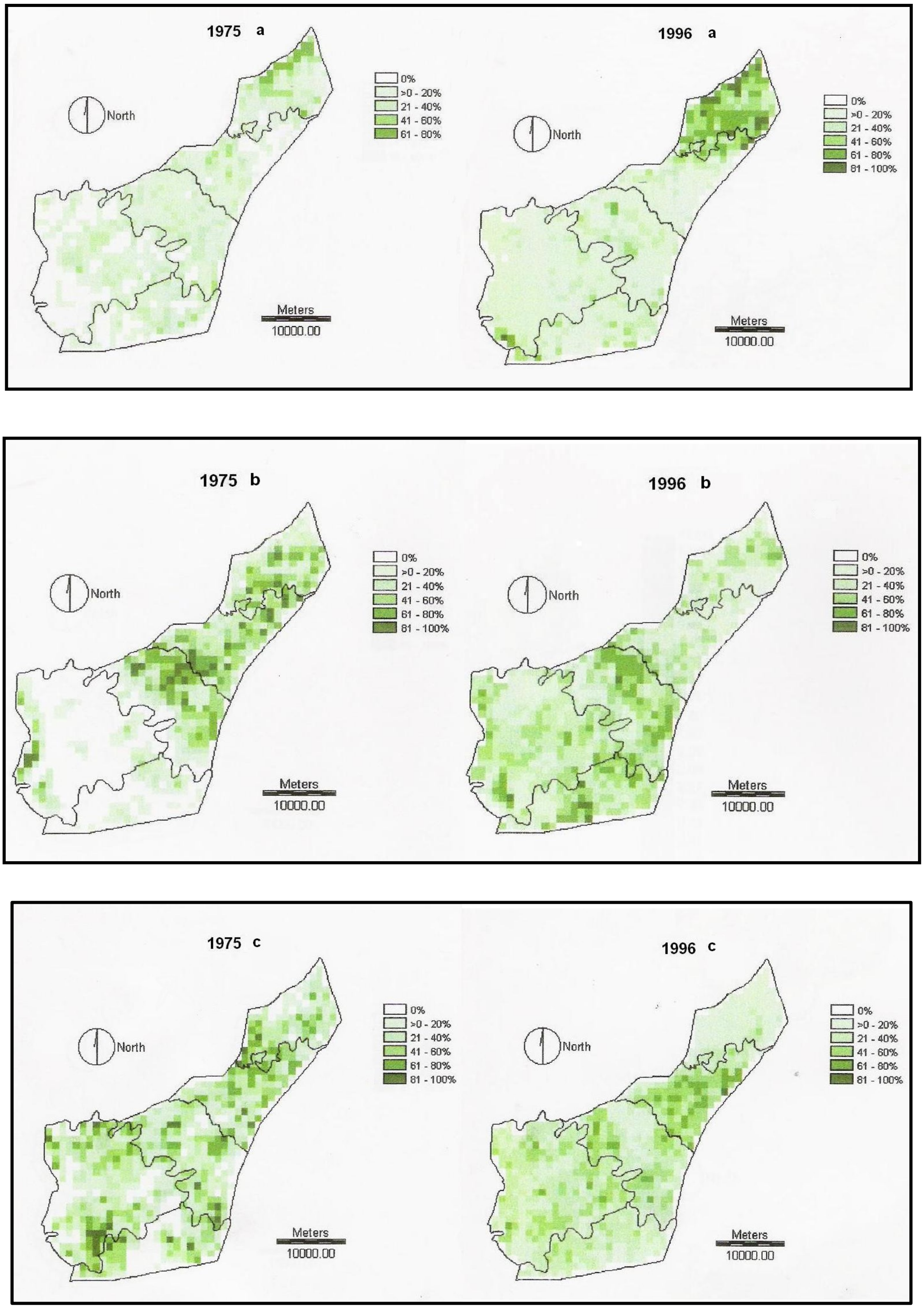
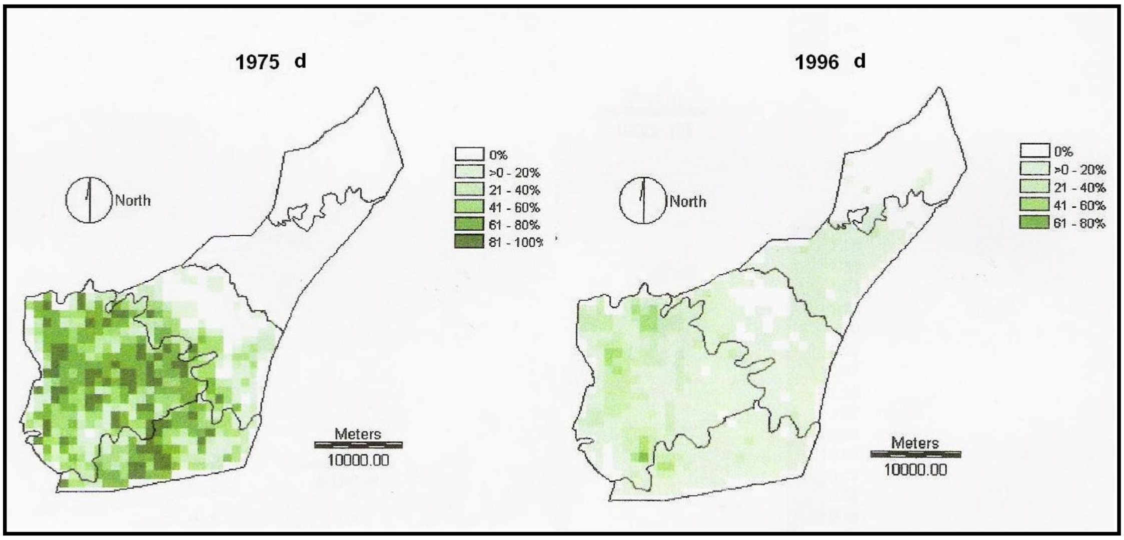


Figure 2.3. Vegetation composition in Hluhluwe iMfolozi Park for the years 1975 and 1996. Five different vegetation classes are shown (a) Forest; (b) Thicket; (c) Woodland (d) Open Woodland; (e) Grassland. Values are given as percentage cover per $1km^2$ grid cell (adapted from Van Niekerk, 2002).



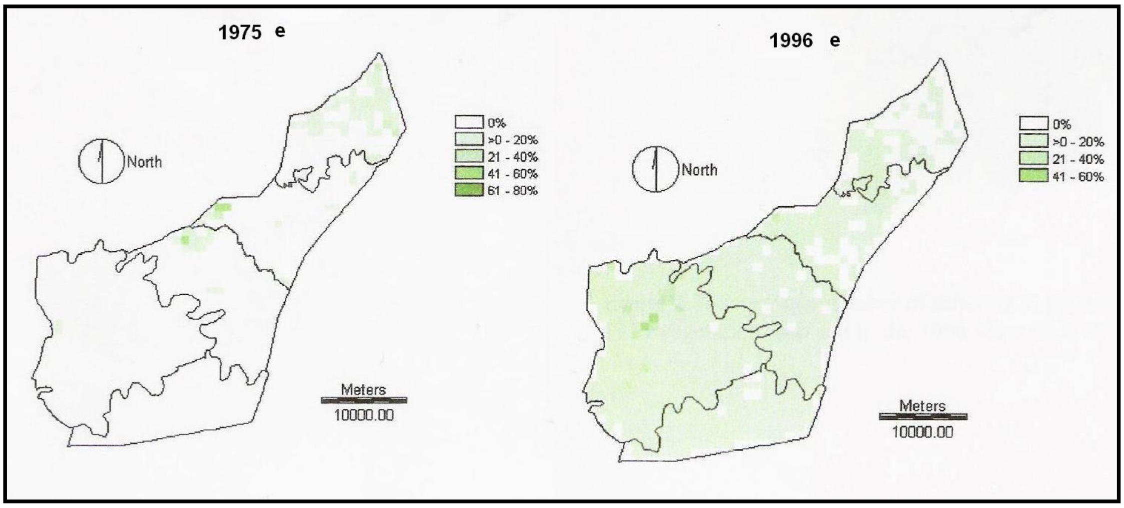


Figure 2.3. (continued). Vegetation composition in Hluhluwe iMfolozi Park for the years 1975 and 1996. Five different vegetation classes are shown (a) Forest; (b) Thicket; (c) Woodland (d) Open Woodland; (e) Grassland. Values are given as percentage cover per $1km^2$ grid cell (adapted from Van Niekerk, 2002).

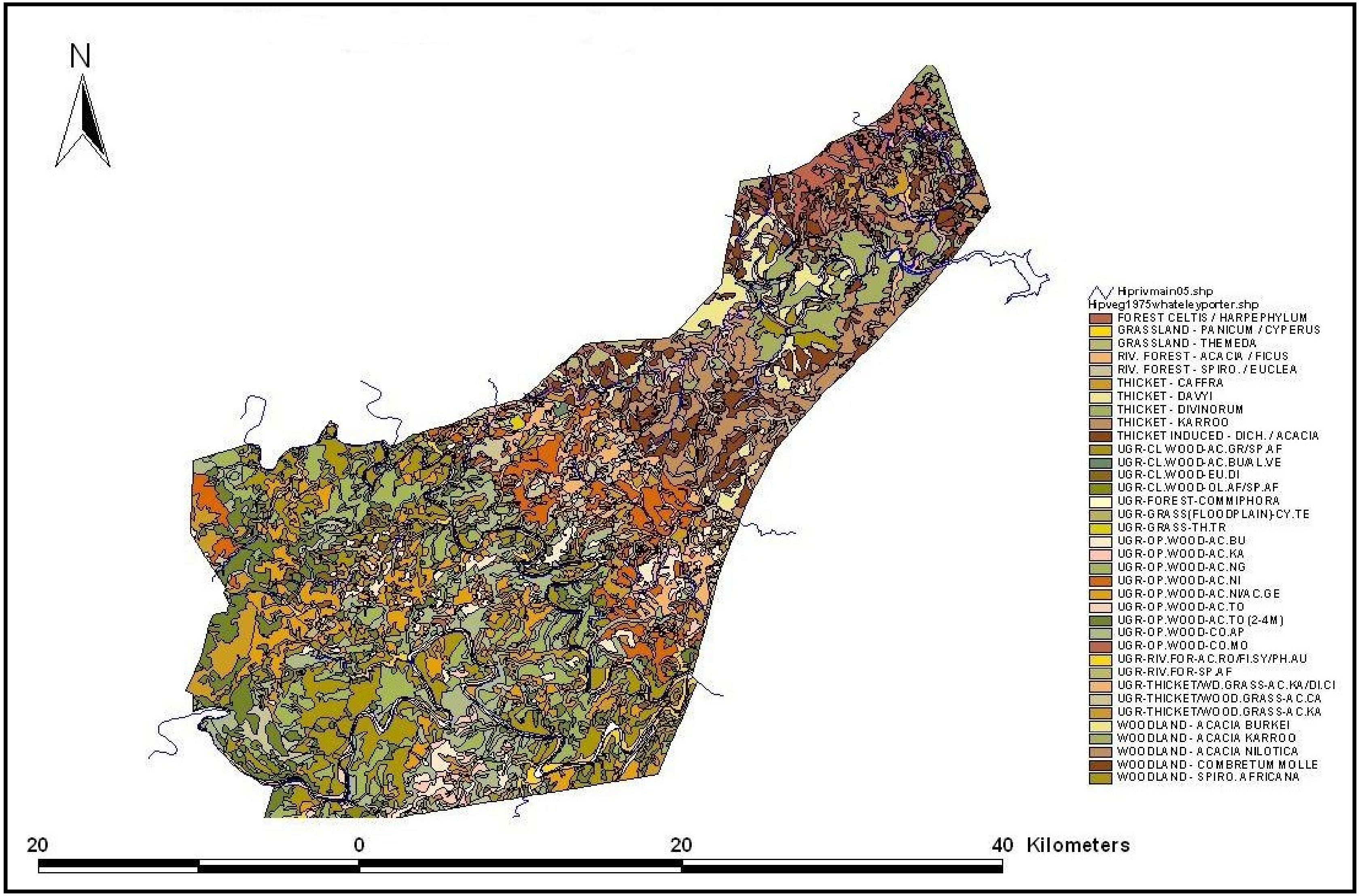


Figure 2.4. Vegetation map of Hluhluwe iMfolozi Park by Whately and Porter (1975).

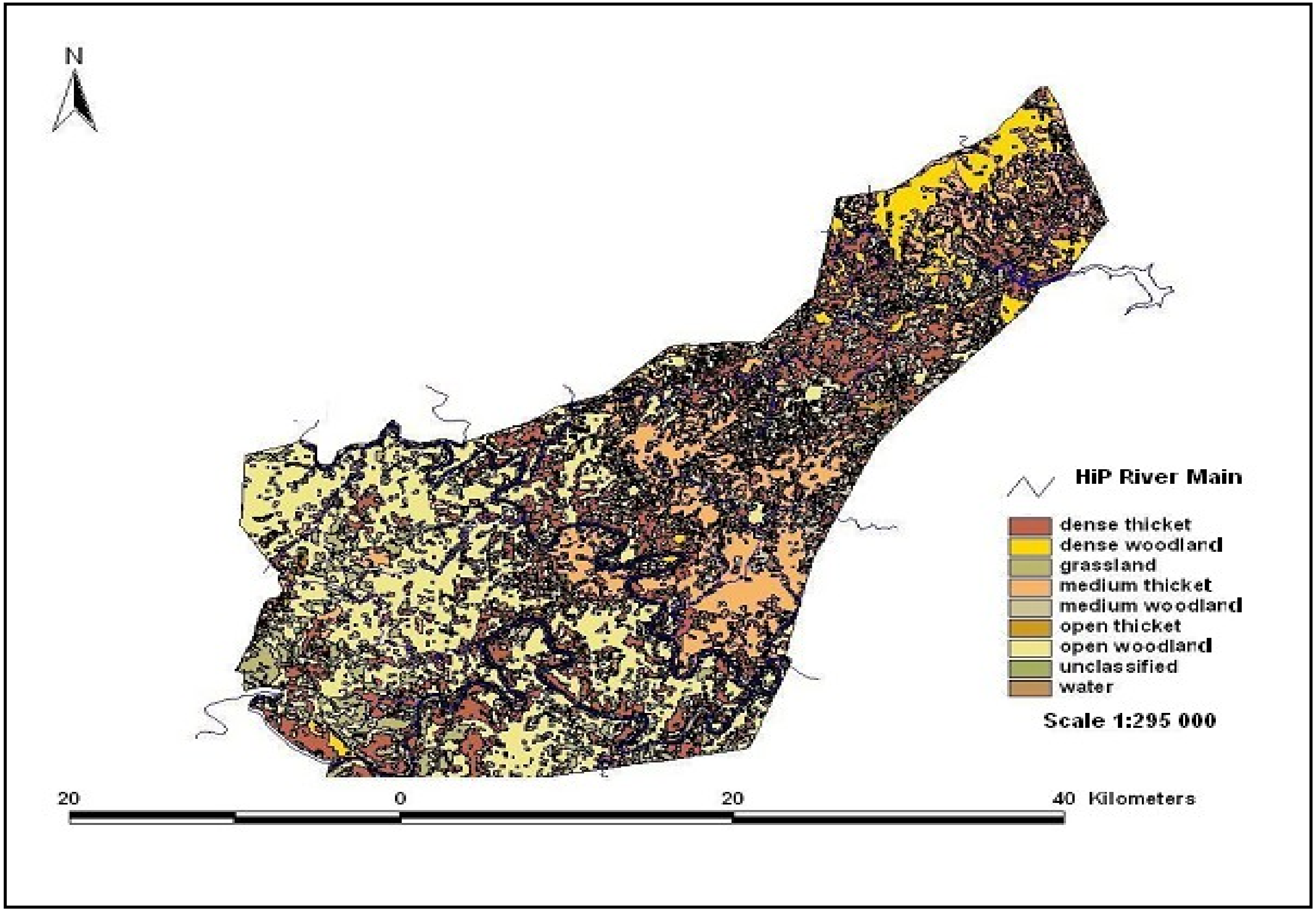


Figure 2.5. Vegetation map of Hluhluwe iMfolozi Park by Dora *et al.* (2001).

2.6. Geology

The geology of HIP is varied. However, most of the area consists of sedimentary deposits, including sandstone (Kruger, 1996). The Hluhluwe section (Figure 2.6) is mainly underlain by sandstone and shale. The rock units found in this section, dip eastward at about 10 degrees, and thus the oldest formations are exposed in the western higher altitude areas (granite) and the youngest along the eastern boundary (basalt) (King, 1970). The Corridor section (Figure 2.7) mainly consists of Ecca group sediments with intrusive dolerite dykes found in areas within the Ecca group, Vryheid formation deposits. Dwyka tillite is found in smaller areas in the higher altitude range of this section. The southernmost section, iMfolozi (Figure 2.8), is underlain by Ecca sediments with intrusive dolerite and basalt areas also present. The minerals present in the bedrock or parent material will have an effect on the soil properties of the area as these will generally also be the constituent minerals of the soil depending on the weathering time of the inherited minerals (Dolgoff, 1996).

2.7. Soil

The various factors that interact in HIP including the climate, topography and geology allow for the wide range of soil forms which are found throughout the area (Figures 2.9 to 2.11). The three sections of HIP have similar soil forms and these are generally related to the geology and terrain position in which they are found. Depth is not a classifying factor and this allows for the same soil forms to be found on differing landscapes, including hillslopes and flatter areas. However, the predominant deeper soils found on the uplands are Hutton and Shortlands, while the shallower Mispah, Glenrosa, Mayo and Milkwood (Soil Classification Working Group, 1991) forms are generally found in the midslopes. Other soil forms including Oakleaf, Valsrivier, Fernwood and Bonheim are dominantly found in lower-lying areas, throughout the Park.

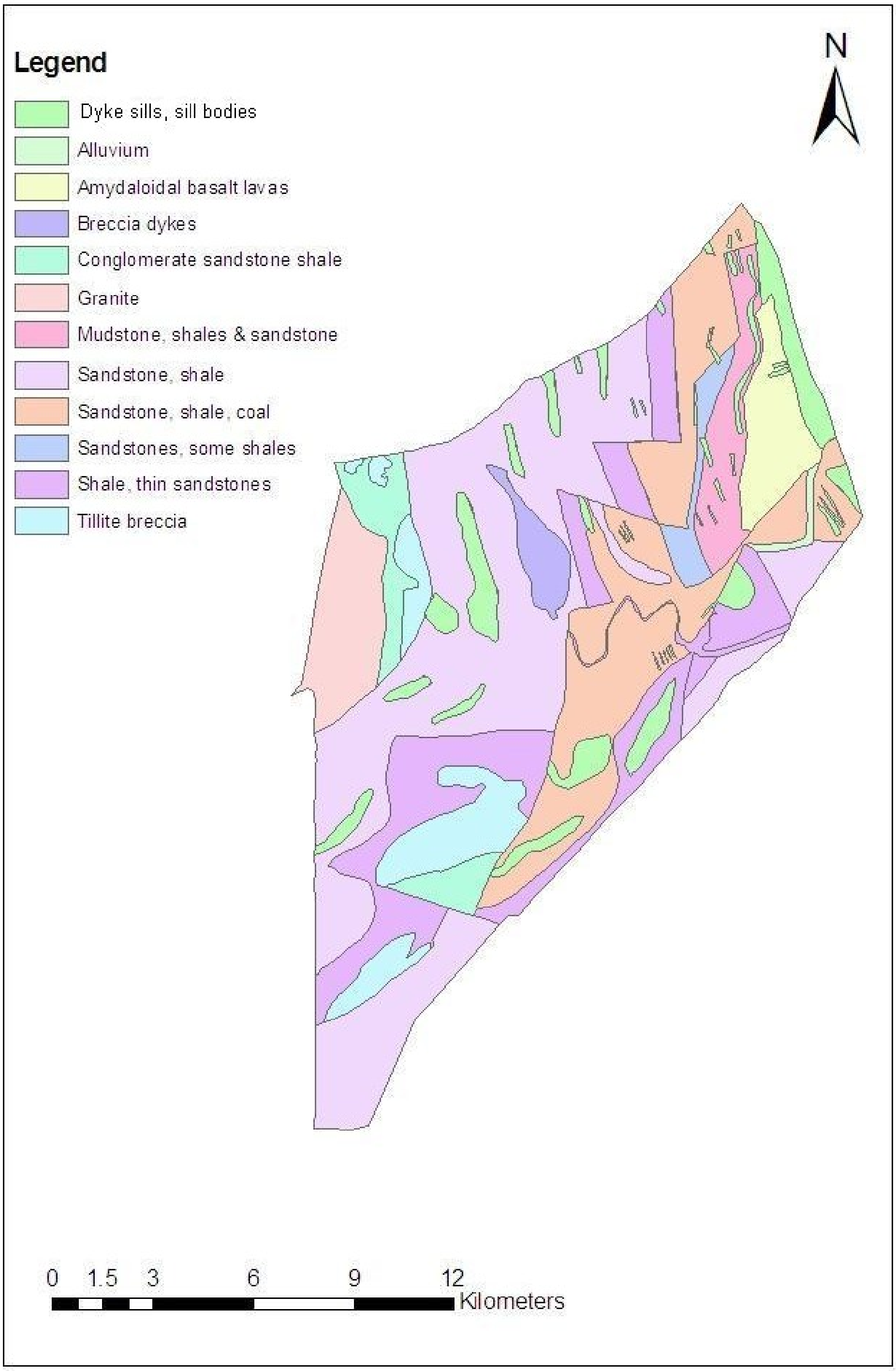


Figure 2.6. Geology of the Hluhluwe section of the Park (from King, 1970)

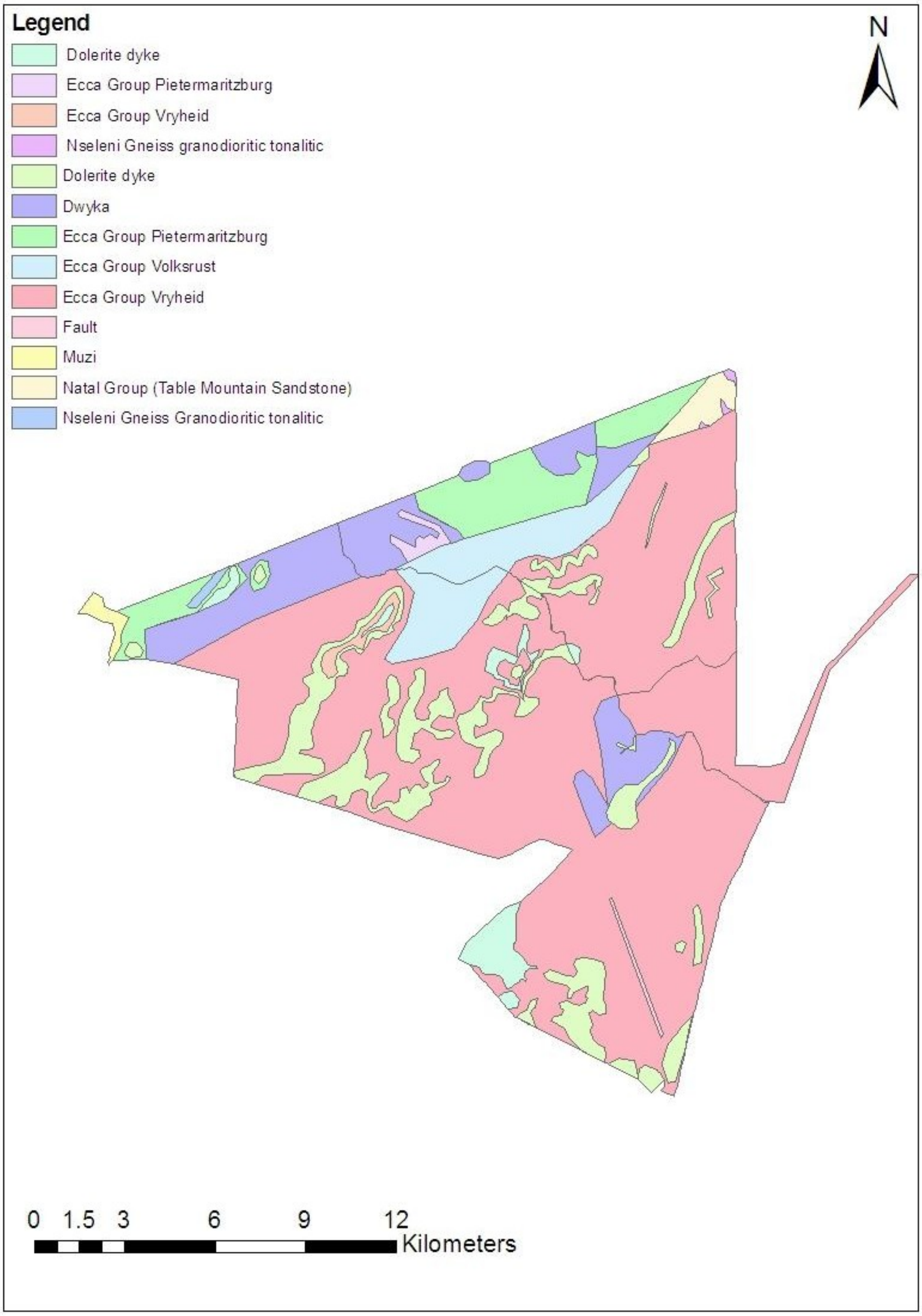


Figure 2.7. Geology of the Corridor section of the park (from Geological Society of South Africa 1998)

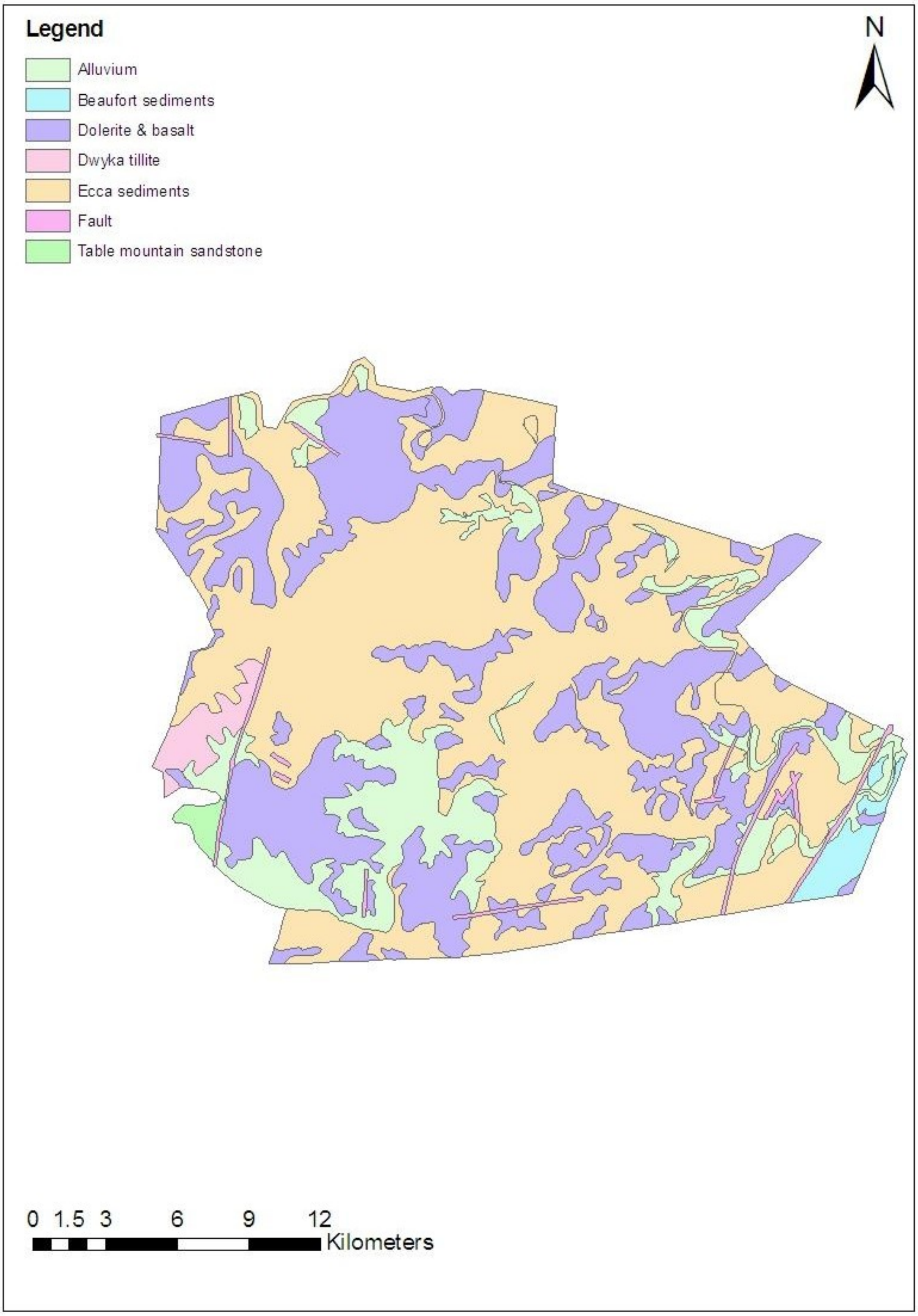


Figure 2.8. Geology of the iMfolozi section of the Park (from Downing, 1980)

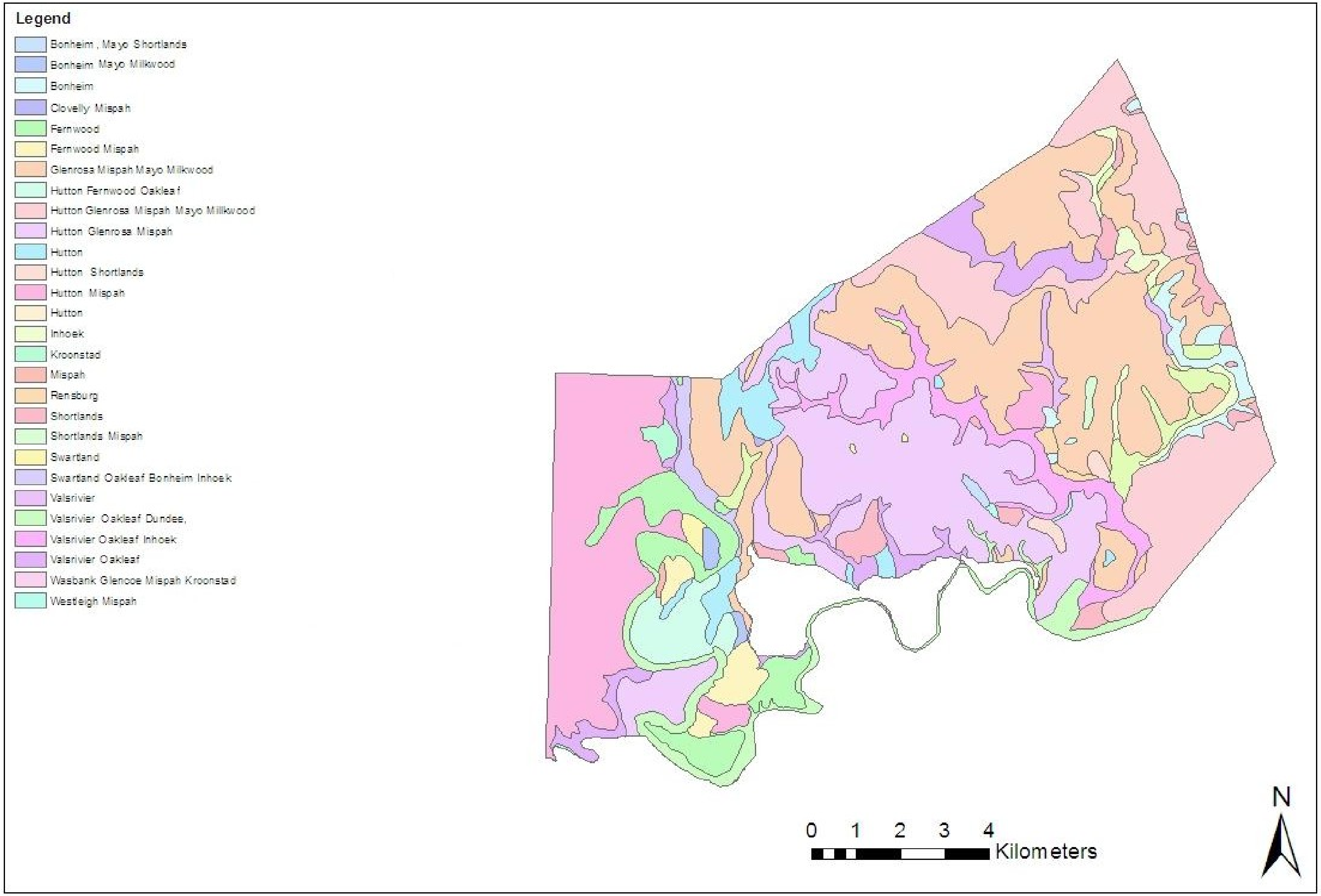


Figure 2.9. Soil forms found in the Hluhluwe section of the Park (from Barrow, 1986)

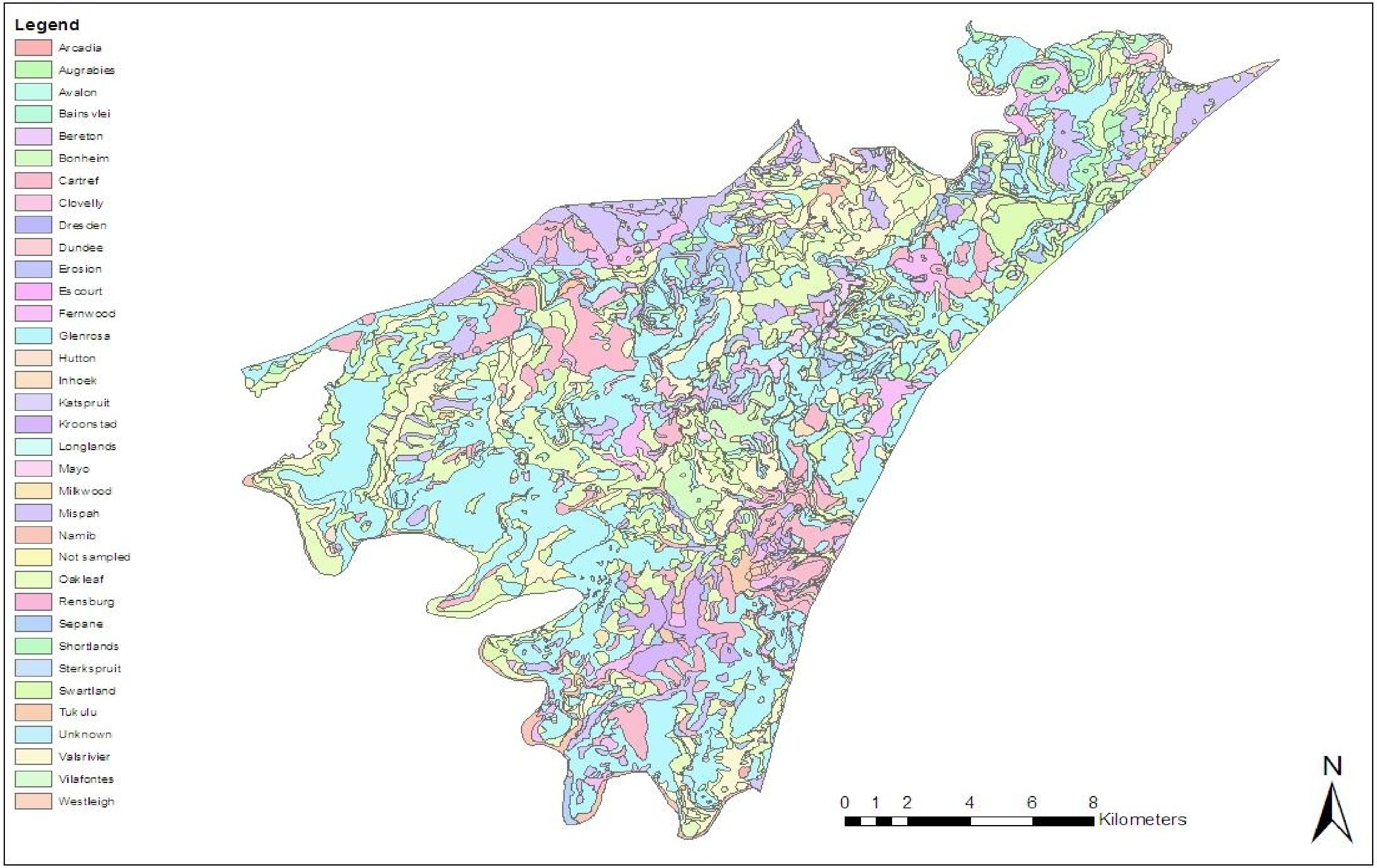


Figure 2.10. Soil forms found in the Corridor and parts of the Hluhluwe section of the Park (mapped from 1998 to 2001, University of Natal)

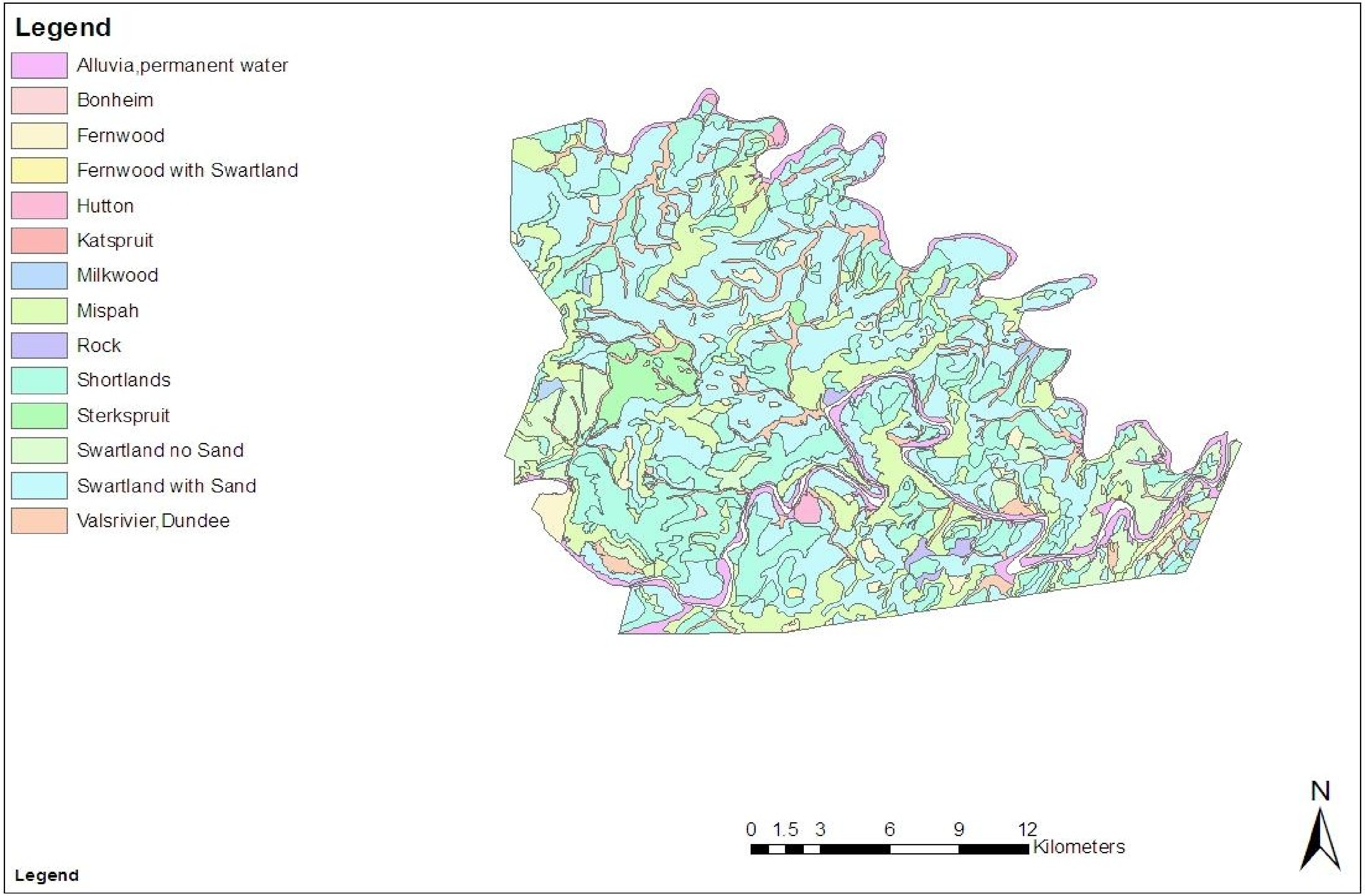


Figure 2.11. Soil forms found in the Imfolozi section of the Park (mapped from 1998 to 2001, University of Natal)

2.8. Fire management

The fire management of Hluhluwe iMfolozi Park has been recorded since the 1950's. However, there are accounts of fire being used in the early 20th Century to manage the vegetation. During the early 1930s and 1940s attempts were made to withhold fire from large areas of HIP during the veterinary tsetse fly eradication programme, to protect the wooden fly traps that had been established. In 1952 fire management was used as a tool to control the encroachment of *Acacia* species (Balfour and Howison, 2001). The burning frequency has been determined to a large extent by the available fuel load and this approach has continued largely unchanged until today (Balfour and Howison, 2001; Archibald *et al*., 2005).

In the mid 1980s a major change in fire management was introduced where a shift occurred from the strict application of the block burning strategy towards an approach whereby fire was used to maintain the structural and temporal patchiness in the vegetation through point source ignition, and broadening the fire season (Balfour and Howison, 2001). Management fires are generally set towards the end of the dry season and most burns occur between July and October. The timing of burns is decided by managers and are usually based on the fuel load of the area. This often results in highly variable fire patterns between years. This is due to much of the grassland areas of HIP being composed of bunch-grass communities which produce a large standing biomass each year and thus are highly flammable (Archibald and Bond, 2003).

Fire intensity is also another aspect of fire management which has been affected due to the fact that fires are managed and do not generally start under natural conditions. This is due to fires seldom being burnt under very hot and dry conditions which can lead to intense and problematic fires. However this is how natural fires would have burnt. Therefore this may suggest fire intensity has decreased since the area was proclaimed a Park and has been a major determinant of the vegetation characteristics.

While the fire management policies have changed throughout the history of the Park the general objectives of burning have remained the same. These are generally to:

- remove the moribund grass material to improve the quality and quantity of resources for grazers;

- manage habitat structure to achieve particular conservation aims (e.g. maintaining browse for black rhino);
- create habitats of different post-fire ages to favour different species;
- assist in controlling alien plant species particularly in the early stages of invasion in a grassland; and
- reduce the build up of a fire hazard situation (Balfour, 1999).

Chapter Three

The relation between physical soil properties determined in the field and the vegetation of Hluhluwe iMfolozi Park

3.1. Introduction

Soil properties that affect the balance between woody and herbaceous vegetation and thus growth patterns in a savanna ecosystem have great implications for the composition, vigour and maturity of members of a plant community (Scholes and Archer, 1997; Sauer *et al*., 2006). The various physical properties of soils including the texture, structure and consistency therefore are key determinants in regulating these patterns (Wu and Archer, 2004). This is due to the physical form of soil playing a large role in influencing the nature of the biological and chemical reactions of the soil and thus influencing plant growth (Worrall, 1960).

The physical properties of soils mainly influence vegetation patterns through their effect on root growth. Soil structure influences the availability of water and nutrients to plants. This can include both a lack of water and thus more oxygen and *vice versa.* However, these properties not only regulate the soil water available to roots and thus the oxygen content but also the nutrient availability. Soil texture and structure therefore are two important properties which can influence the vegetation composition in a particular area. Soil colour, on the other hand, is a useful property for indicating other factors such as drainage and aeration within the profile (Gourlay and Tunstall, 1994). Through identifying these features in the field, the properties of soils can be related to the vegetation growth patterns in an area. Through classifying the soil to its form and family level, patterns can be sought in order to understand if a relationship exists between specific soil properties and vegetation communities. The aims of this chapter are to determine if any physical soil properties are related to changes in tree density patterns throughout Hluhluwe iMfolozi Park over the past two decades.

3.2. Materials and Methods

3.2.1. Site locations

The changing vegetation growth patterns in Hluhluwe iMfolozi Park have been observed on a continuous basis. This has been achieved through the use of a series of fixed-point photographs, taken every four years between 1974 and 1997, to show the vegetation dynamics throughout the Park and thus changes that have occurred in particular areas.

These photographs were used to identify sites where a change had occurred over this period. The photographs were scanned into a database using CorelDraw and used to choose fourteen sites, which show either a 'change' or 'no-change' in vegetation in an area over this period. This was achieved through visually observing and assessing the photographs. Percentage of change in tree density was estimated by looking at the fixed point photographs from 1974 and 1997. The percentage of change in tree density that had occurred within a specific area shown in the photograph was used to determine the change which had taken place. The number of sites sampled was a function of the accessibility of the sample area and the distribution of the changes which had taken place within the Park. The sites are situated in four of the five management sections (Figure 3.1) and thus represent a wide area of the Park. Examples of these are shown in Figures 3.2 to 3.6. Aerial photographs of the sites and transects completed at each site are given in Appendix 1. The fourteen sites are comprised of:

- 4 sites where 'no change' (0-4%) in vegetation had occurred
- 2 sites where a 'slight increase' (5-20%) in tree density had occurred
- 3 sites where a 'greater increase' (>20%) in tree density had occurred
- 2 sites where a 'slight decrease' (5-20%) in tree density had occurred
- 3 sites where a 'greater decrease' (>20%) in tree density had occurred

These sites were then located in the field within the Park, and given a number according to their location as shown on maps provided by Ezemvelo-KZN Wildlife. The numbers of the sites and the category of change they are found in are summarized in Table 3.1.

As each site was located, it was given a GPS coordinate. These were then used to position the site on aerial photographs, using ArcMap version 9. Aerial photographs showing a one kilometre area around the site of the fixed point photograph were created and used to determine the number of transects needed and the length of each transect in order to cover the area of change shown in the photograph. This was due to the variability in size of the area shown in the photographs and the fact that at some sites the sample transects only covered the area of change, as opposed to the entire area shown in the photograph. A one kilometre sample area was chosen to standardize the sample area per site.

3.2.2. Soil sampling and field data collection

The number of points along each transect differed between sites and depended on the variability in environmental factors specific to a site and included the topography and vegetation cover (Appendix 1). At each point along each transect, the soil was augered to a depth of 120 cm or until the bedrock was reached if this was shallower. The classification of the soil was then carried out at each point according to the Soil Classification Working Group (1991). The soil was divided into its respective horizons, and 500g of each horizon collected as a sample.

The field texture, the depth of each horizon and profile, the Munsell colour, and the structure, were also recorded at each point for each horizon. Each point along each transect was also given a GPS coordinate, so that maps of the areas sampled could be created.

3.2.3. Determination of field soil properties

The field texture was determined through feel (Soil Survey Division Staff, 1993) to obtain an estimate for each horizon. The Munsell colour was determined for both dry and moist samples of each horizon using the Munsell Soil Colour Charts (Munsell Color, 2000). The structure of each horizon was placed into one of five size classes, namely very fine, fine, medium, coarse and very coarse. The degree of aggregation was determined and placed into one of four groups i.e. structureless, weak, moderate and strong. The type of structure was also noted and placed into one of four classes i.e. structureless, spheroidal, blocky and prismlike (Soil Survey Division Staff, 1993).

Table 3.1. The category of change and site number sampled in Hluhluwe iMfolozi Park

Category	Site number	Section of Park
No change (0%-4% change)	0894	Hluhluwe
No change (0%-4% change)	0898	Hluhluwe
No change (0%-4% change)	8168	iMfolozi
No change (0%-4% change)	9570	Corridor
Slight Increase (5%-20% change)	0479	Corridor
Slight Increase (5%-20% change)	9782	Corridor
Increase (>20% change)	9579	Corridor
Increase (>20% change)	0994	Hluhluwe
Increase (>20% change)	7561	iMfolozi
Slight Decrease (5%-20% change)	9574	Corridor
Slight Decrease (5%-20% change)	8278	iMfolozi
Decrease (>20% change)	9985	Corridor
Decrease (>20% change)	8376	iMfolozi
Decrease (>20% change)	0991	Hluhluwe

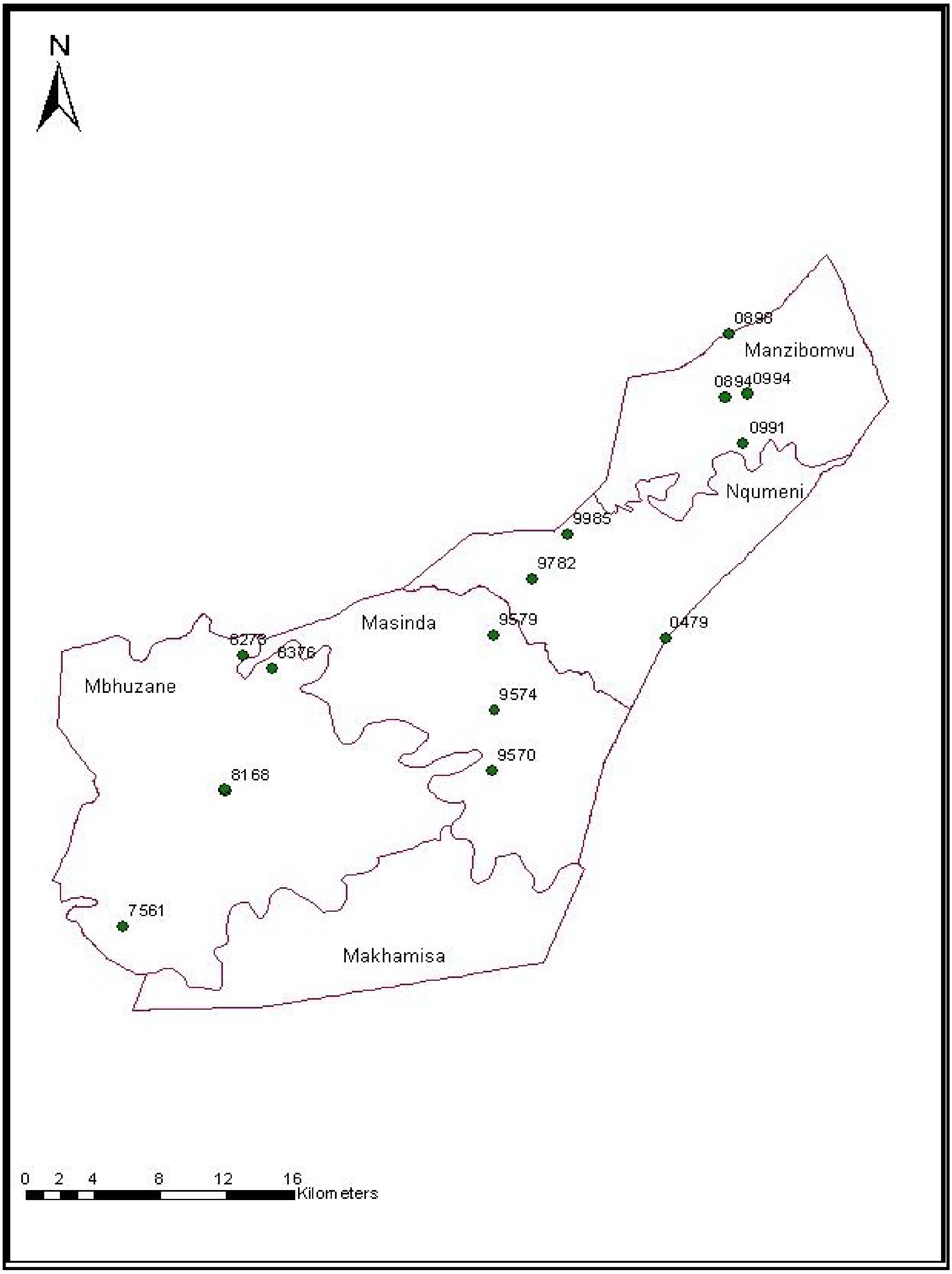


Figure 3.1. The location of the sites sampled in Hluhluwe iMfolozi Park

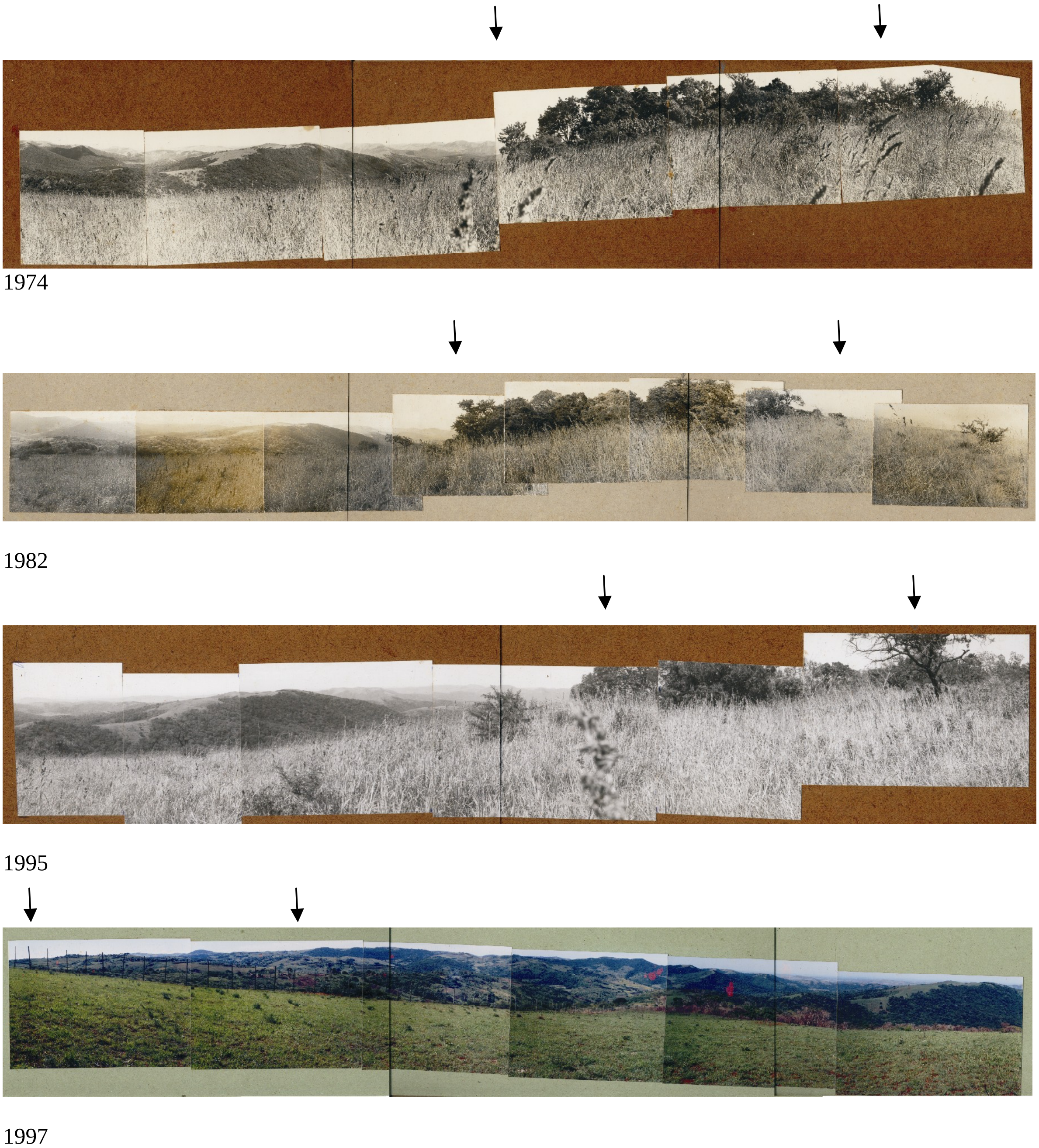


Figure 3.2. An example of the fixed point photographs used to assess the ‘no-change’ in vegetation at site 0898. The area between the arrows is the part of the photograph, which was sampled

1974

1982

1995

1997

Figure 3.3. An example of one of the ‘slight increase’ at vegetation site 0479. The area to the left of the road was sampled

1974

1982

1995

1997

Figure 3.4. Fixed point photographs showing an example of one of the ‘increase’ at vegetation site 7561. The hill shown by the arrow has had an increase in tree density and was the sample area

1974

1978

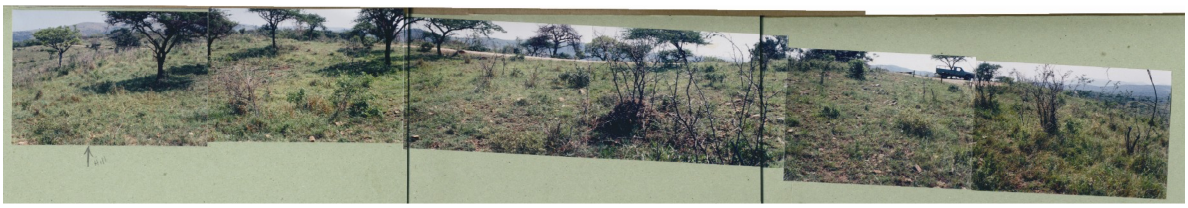
1982

Figure 3.5. Fixed point photographs showing an example of a ‘slight decrease’ in vegetation at site 9574.

1974

1982

1995



1997

Figure 3.6. Fixed point photographs showing an example of a ‘decrease’ in vegetation site, 9985. The area shown in the foreground of the photograph was sampled

3.2.4. Statistical analysis

Due to the likely interactions between many of the variables measured both in the field and laboratory that cannot be tested for statistically it was decided to utilise statistical models determined using Canoco for Windows 4.5 and run using a principal component analysis (PCA). The type of horizon, horizon boundary, structure type, colour group, and depth for the top and subsoil were included in the models and were analysed against the site category. This allows one to see which soil properties were associated with the various site categories. Names used in the PCA analysis are given in more detail in Table 3.2.

The Munsell colours recorded for the dry samples where placed into a group using the method of Coventry and Robinson (1981). The groups are a generalised view based on the hue, value and chroma and help give a description of the various colours associated with the local soil conditions at each site. The group numbers also enable the use of colour as a soil property in the statistical analysis.

The data collected in the field including the soil form, type of horizon, horizon boundary, structure class, colour group and depth for the top and subsoil were also condensed down through univariate analysis. The frequency of each of the above was calculated and plotted on a bar graph for both the top and subsoil for all site categories (Appendix 2).

3.3. Results

3.3.1. Principal Component Analysis

The PCA results obtained for all sites across the Park (Figures 3.7 to 3.16), give an indication of the type of soil properties associated with the different sites sampled. The 'no change' sites 0894, 8168 and 9570 are linked to similar soil characteristics in the top and subsoil (Figure 3.7 and 3.8) including structure classes such as granular and a Lithocutanic B horizon due to the presence of the Glenrosa soil form. The depth of the soil profile is most closely linked with the 0898 site in the subsoil (figure 3.8) and this is due to the prevalence of the deeper Hutton soil forms found in this area. This can also be seen in the occurrence of the red apedal B horizon which is attributed to this soil form.

The sites classified as having an ‘increase’ in vegetation, are closely linked to the crumb and granular structures in the topsoil (Figure 3.9). The site 0479 is closely associated with the E horizon and single grain structure (Figure 3.10) due to the occurrence of the Fernwood soil form at this site. Site 7561 is related to the sharp horizon boundary (Figure 3.11) due to the high frequency of the Mispah soil form. It is also associated with the pedocutanic B horizon along with 9579 (Figure 3.12).

The sites classified as a ‘decrease’ in vegetation are linked to the structure of the soil as shown in the single grain structure type being associated with the 8278 site (Figure 3.13) due to the occurrence of the Hutton and Oakleaf soil forms. This can also be seen in the link between the neocutanic horizon type and gradual horizon boundary with site 8278 (Figure 3.14). Sites such as 0991 and 9985 are not closely associated with any distinct soil characteristics due to the diversity of the soil forms that were found at these sites (Figure 3.15). The sub-angular blocky structure is related to site 8376 (Figure 3.16), due to the pedocutanic B horizon found in the soils formed here, including the Swartland form. The granular structure is also found to be linked to this site due to the occurrence of the Mispah, Oakleaf and Valsrivier soil forms.

3.3.2 Soil texture, structure and horizon boundary

A number of soil field texture classes were found in all sample areas across HIP. However, the most prominent types consist of sandy loam, loam, clay loam and silt loam for both the top and subsoil for all site categories. The texture classes were also compared across the Hluhluwe, Corridor and iMfolozi sections. The dominant textures in the Hluhluwe and Corridor sections are loam, clay loam and silt loam for both top and subsoils. Sites sampled in the iMfolozi section appear to have textures mainly associated with the clay loam and sandy loam classes.

Table 3.2. Description of names shown in PCA analysis.

Name given in PCA chart	Site category	Structure name	Name of horizon	Horizon boundary type
0894	X			
0898	X			
8168	X			
9570	X			
9782	X			
0479	X			
9579	X			
0994	X			
7561	X			
0991	X			
9985	X			
8376	X			
9574	X			
8278	X			
Melanic A			X	
Orthic A			X	
Vertic A			X	
E			X	
G			X	
Lithocutanic B			X	
Pedocutanic B			X	
Red Apedal B			X	
Neocutanic B			X	
Sharp Horizon Boundary				X
Distinct Horizon Boundary				X
Gradual Horizon Boundary				X
Granular		X		
Sub-angular blocky		X		
Crumb		X		
Single grain		X		

The structure class of the soil varies from apedal to sub-angular blocky and blocky across all site categories. The sub-angular blocky, granular and crumb structure which are associated with a moderate structure appear to be the most dominant type in all categories for the topsoil and the single-grain and sub-angular blocky classes the main type for the subsoil.

The horizon boundaries can affect vegetation patterns through contrasting soil properties which are found in each horizon, as these could impede root growth. The abrupt boundary which is a prominent type in all three sections of the Park, particularly so in iMfolozi, is generally associated with the Mispah soil form as this consists of an A horizon over bedrock. The gradual and distinct boundaries, which are more associated with Swartland and Oakleaf soils, respectively, are more prominent in the Corridor and Hluhluwe sections (Appendix 3)

3.3.3 Soil colour

The colour groups of the soil samples fall within a wide range and are associated with the local soil conditions of the site. The hues associated with the Munsell colours are mainly yellower than 2.5YR and the values and chromas are mostly within the range of 3-5 and 2-6, respectively. The groups of colours found at the sites sampled generally fall within Groups 1 and 2 for all site categories for the topsoil, which are associated with the dark colours and browns, respectively (Appendix 4).

3.3.4. Soil form

The frequency of soil form compared against the site category show that the no change category are predominantly associated with the Mispah, Glenrosa, Hutton, Oakleaf and Bonheim soil forms. The Mispah soil form is a dominant form across all sites with the Oakleaf form also occurring in all categories but to a lesser extent. The Valsrivier form occurs in 'decrease' category sites and the Swartland form is the most common in 'increase' category sites.

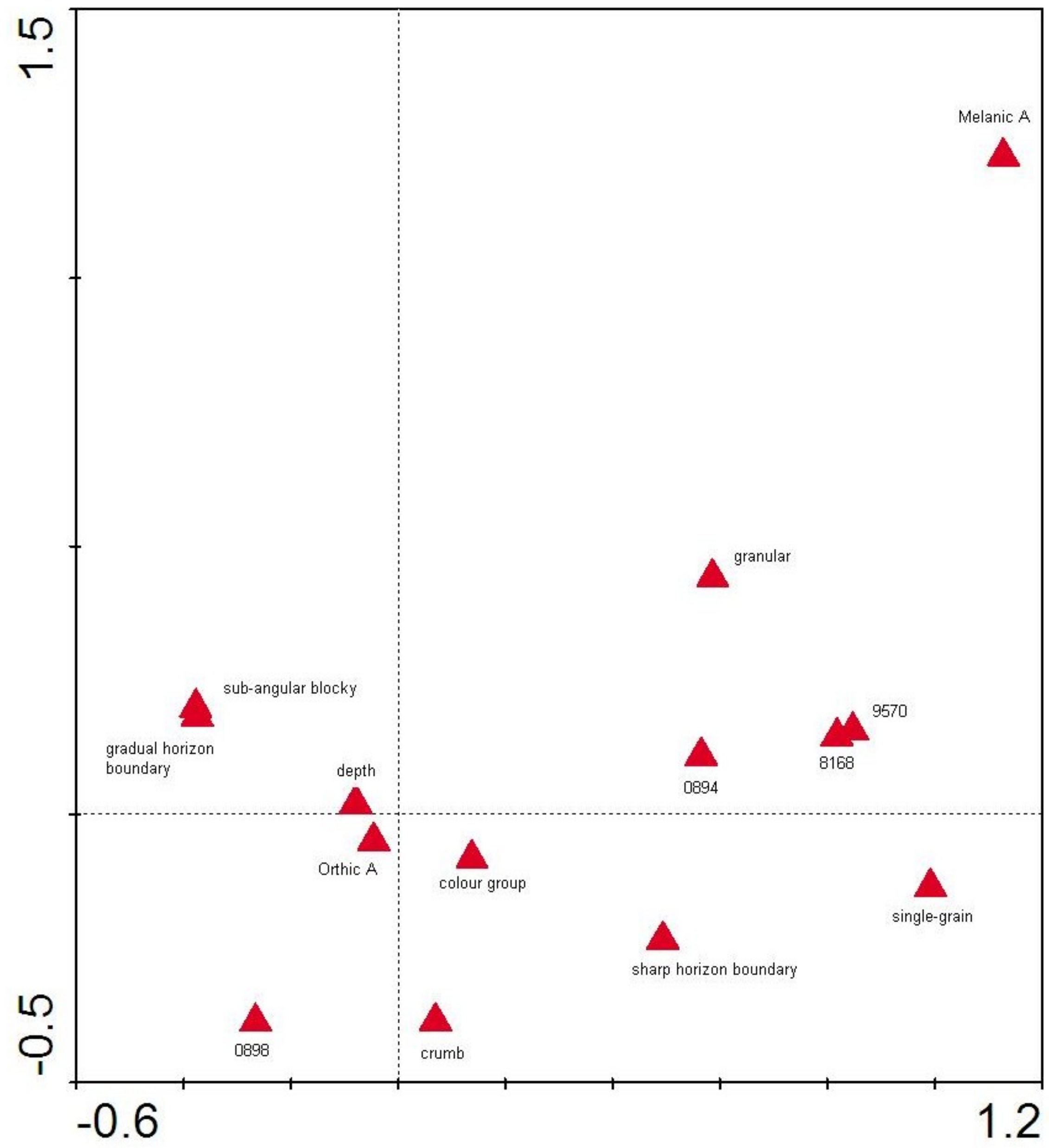


Figure 3.7. Standardised and centered PCA data of the topsoil data collected for the 'no-change' in vegetation density sites. Eigenvalues: (1) 0.331 (2) 0.173. Total percentages represented by the first two axes is 50.4.

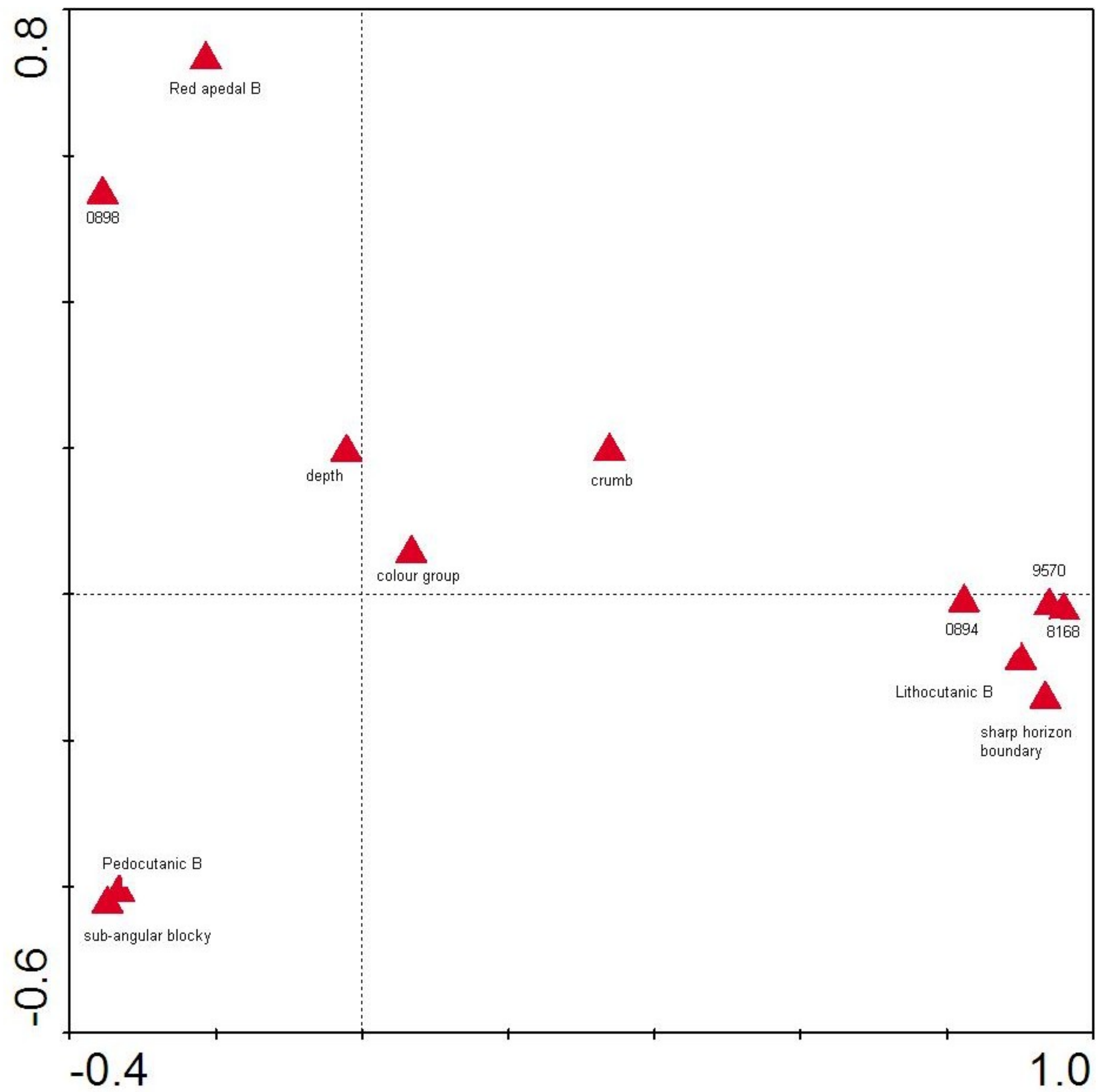


Figure 3.8. Standardised and centered PCA of the subsoil field properties determined in the 'no-change' in vegetation density sites. Eigenvalues: (1) 0.235 (2) 0.201. Total percentages represented by the first two axes is 43.6

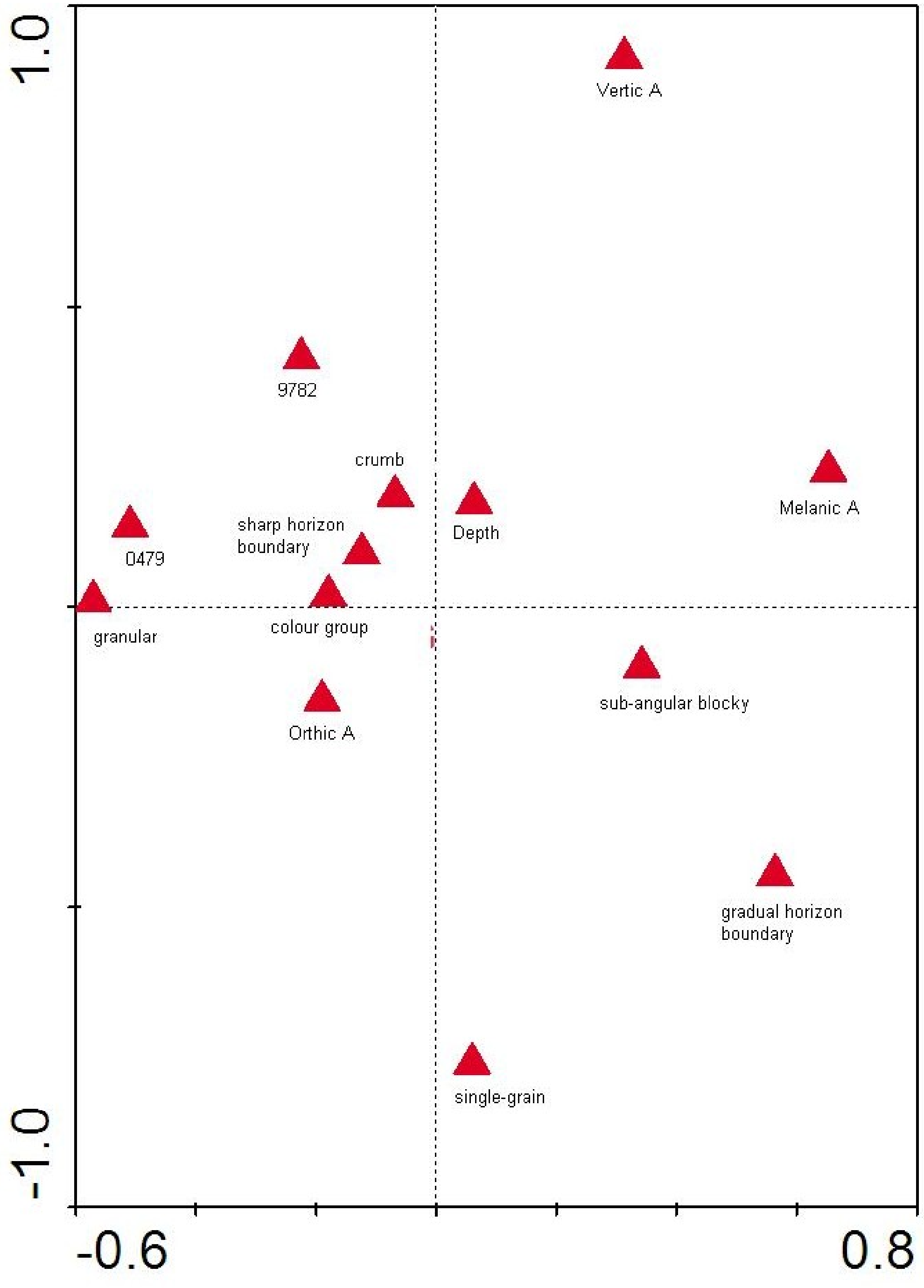


Figure 3.9. Standardised and centered PCA of the topsoil data collected for the 'slight increase' in tree density sites. Eigenvalues: (1) 0.221 (2) 0.171. Total percentages represented by the first two axes is 39.2

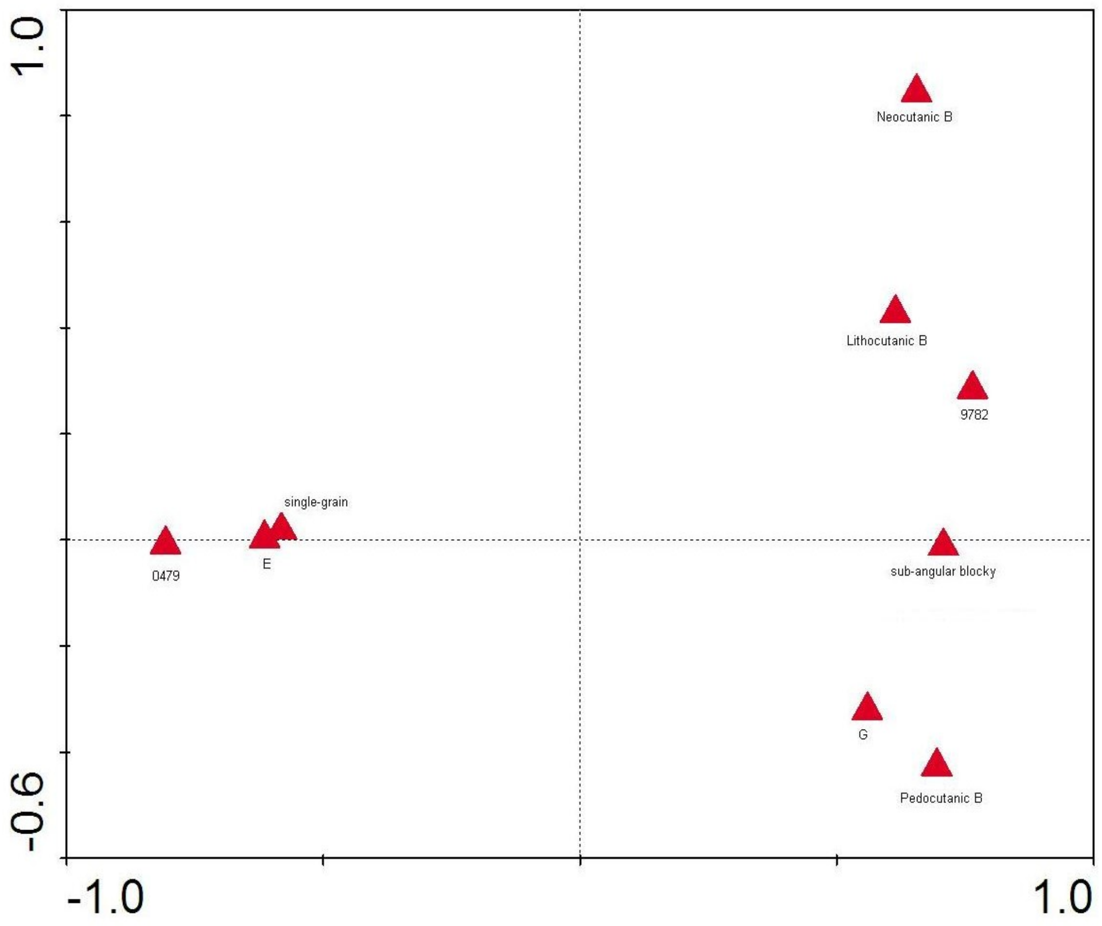


Figure 3.10. Standardised and centered PCA of the subsoil data collected for the ‘slight increase’ in tree density sites. Eigenvalues: (1) 0.431 (2) 0.138. Total percentages represented by the first two axes is 56.9

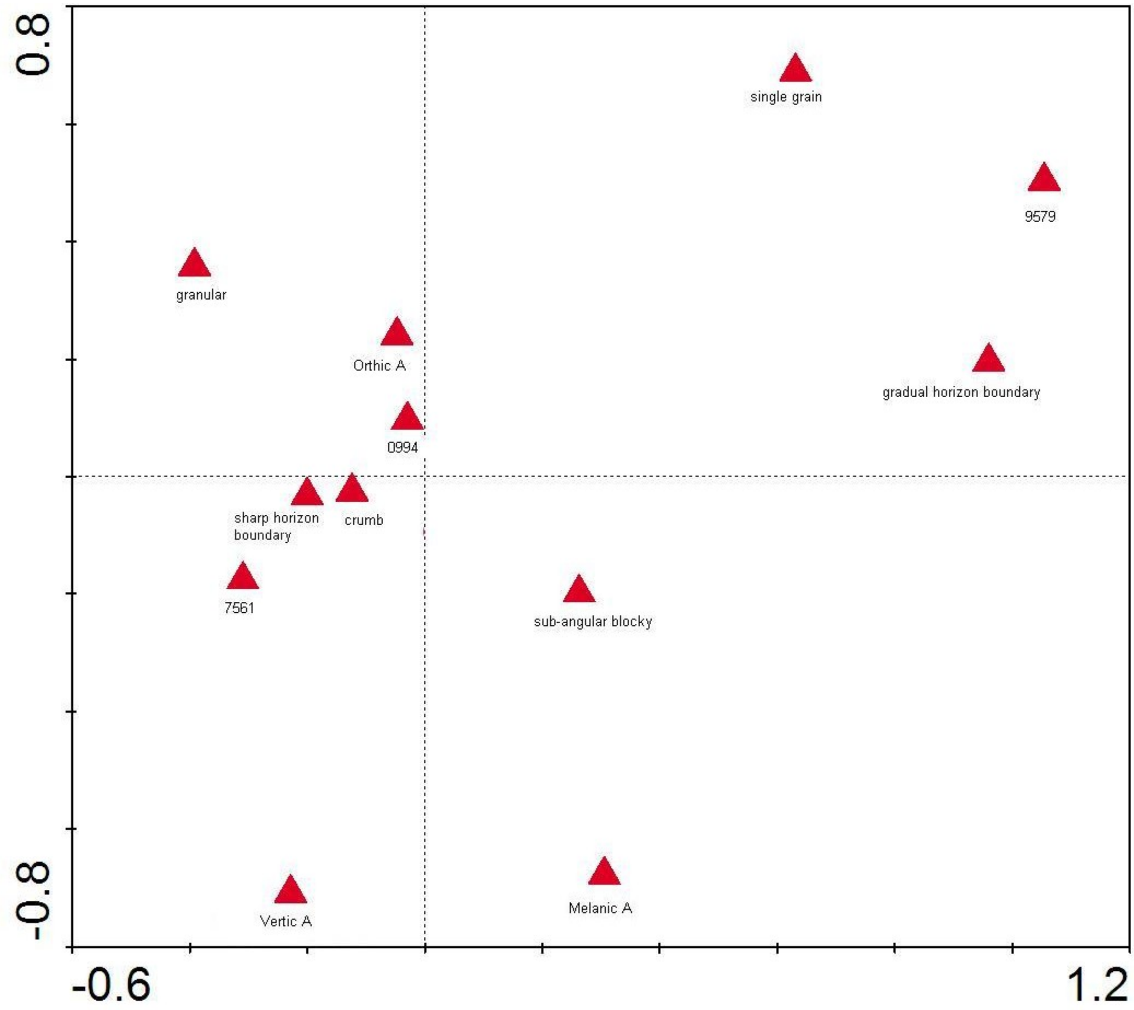


Figure 3.11. Standardised and centered PCA of the topsoil data collected for the 'increase' in tree density sites. Eigenvalues: (1) 0.235 (2) 0.191. Total percentages represented by the first two axes is 42.5

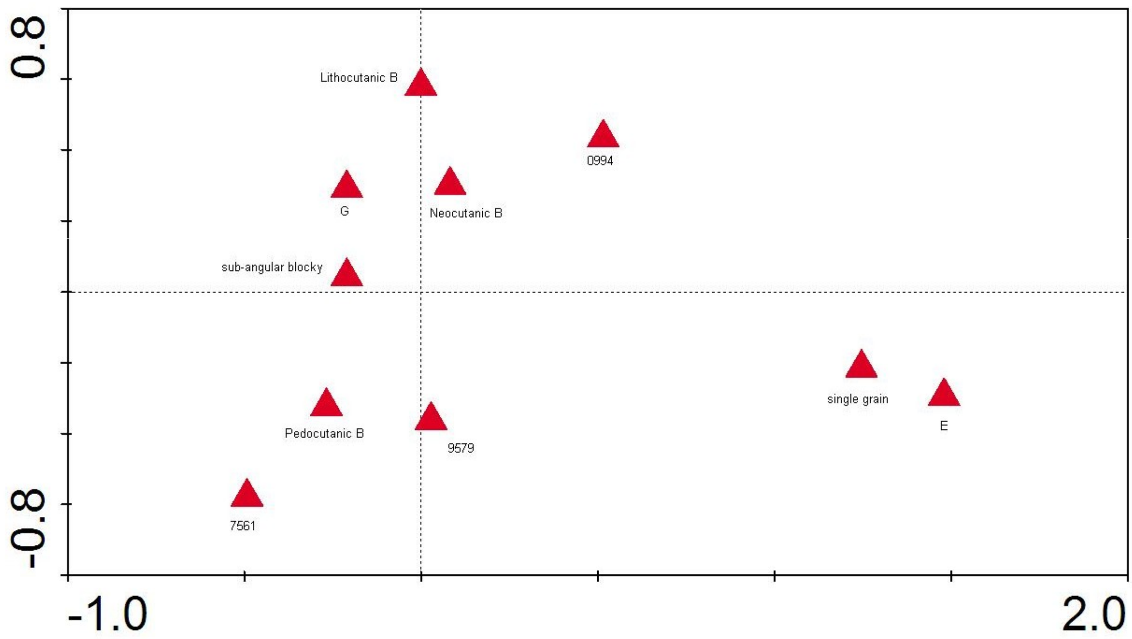


Figure 3.12. Standardised and centered PCA of the subsoil data collected for the 'increase' in tree density sites. Eigenvalues: (1) 0.289 (2) 0.177. Total percentages represented by the first two axes is 46.6

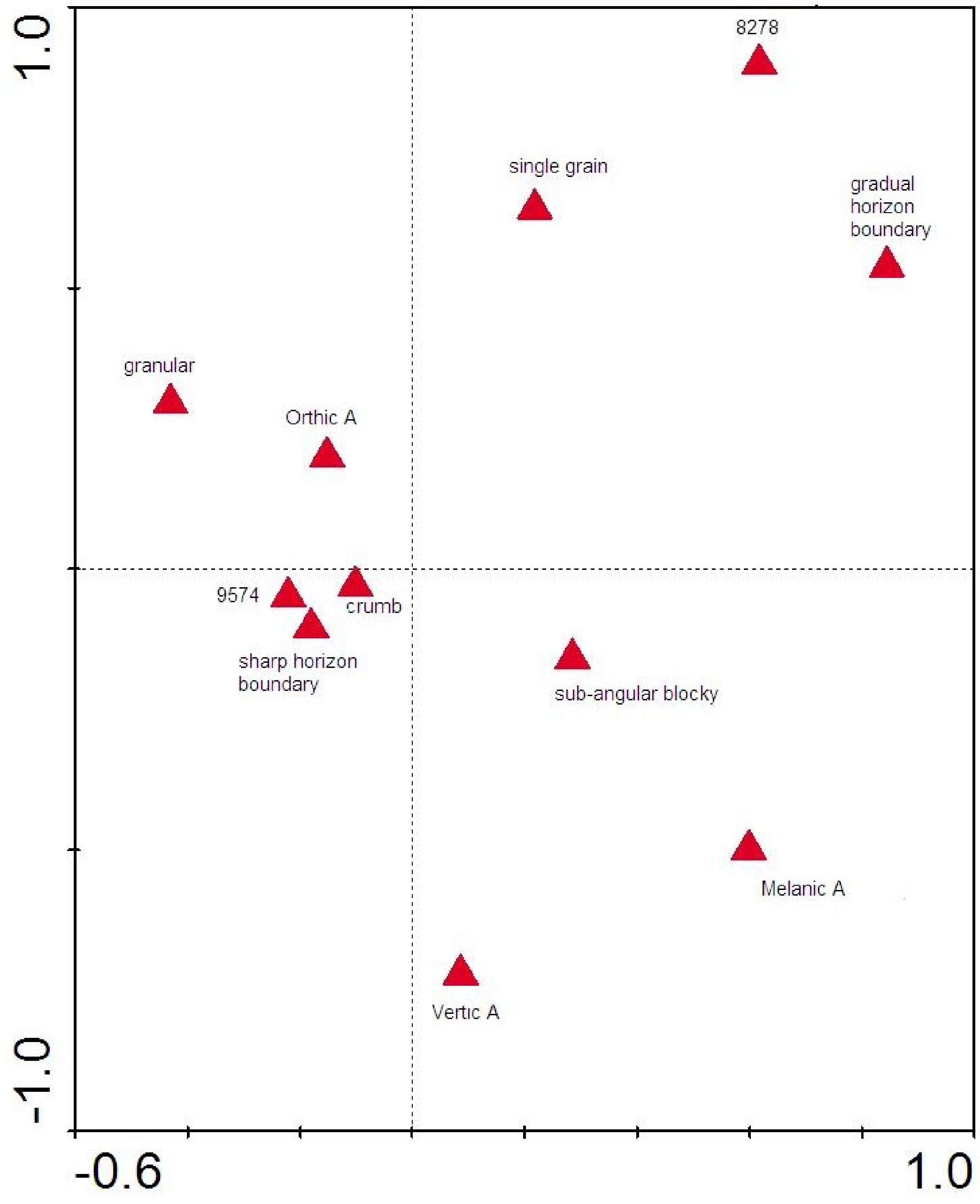


Figure 3.13. Standardised and centered PCA of the topsoil data collected for the 'slight decrease' in tree density sites. Eigenvalues: (1) 0.235 (2) 0.201. Total percentages represented by the first two axes is 43.6

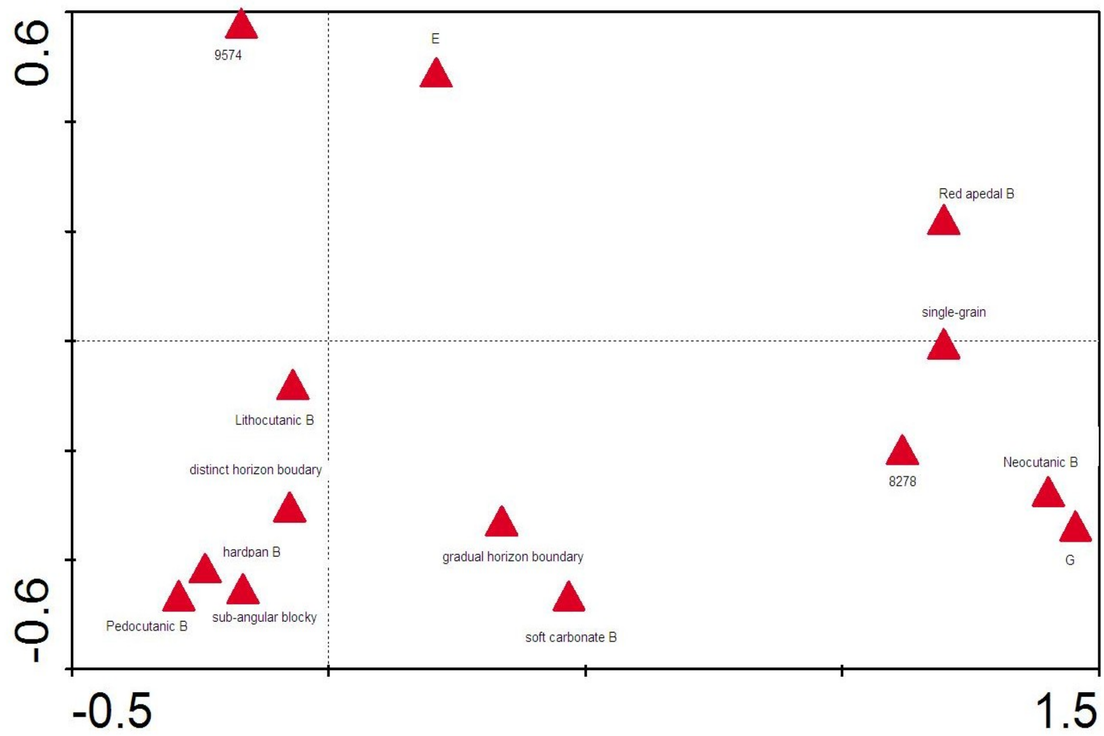


Figure 3.14. Standardised and centered PCA of the subsoil data collected for the 'slight decrease' in tree density sites. Eigenvalues: (1) 0.244 (2) 0.183. Total percentages represented by the first two axes is 42.7

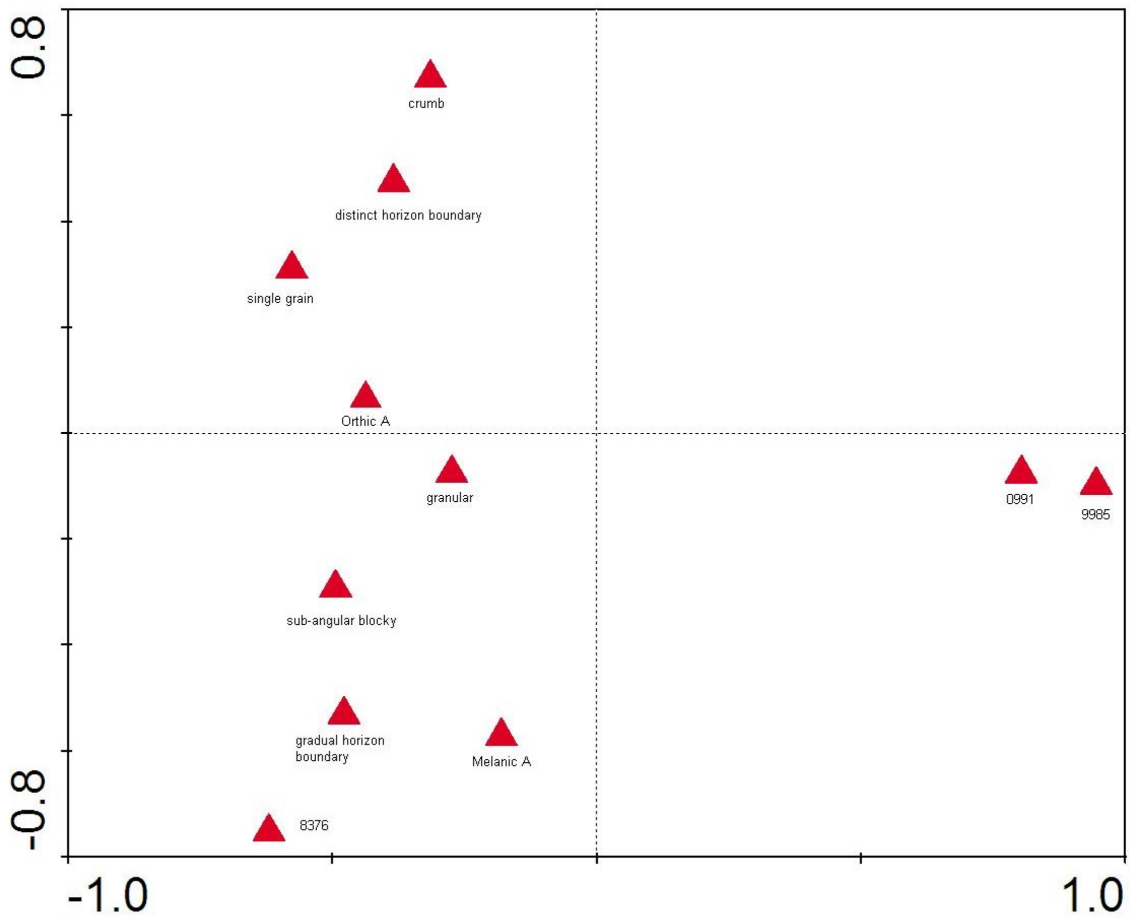


Figure 3.15. Standardised and centered PCA of the topsoil data collected for the 'decrease' in tree density sites. Eigenvalues: (1) 0.305 (2) 0.205. Total percentages represented by the first two axes is 51.1

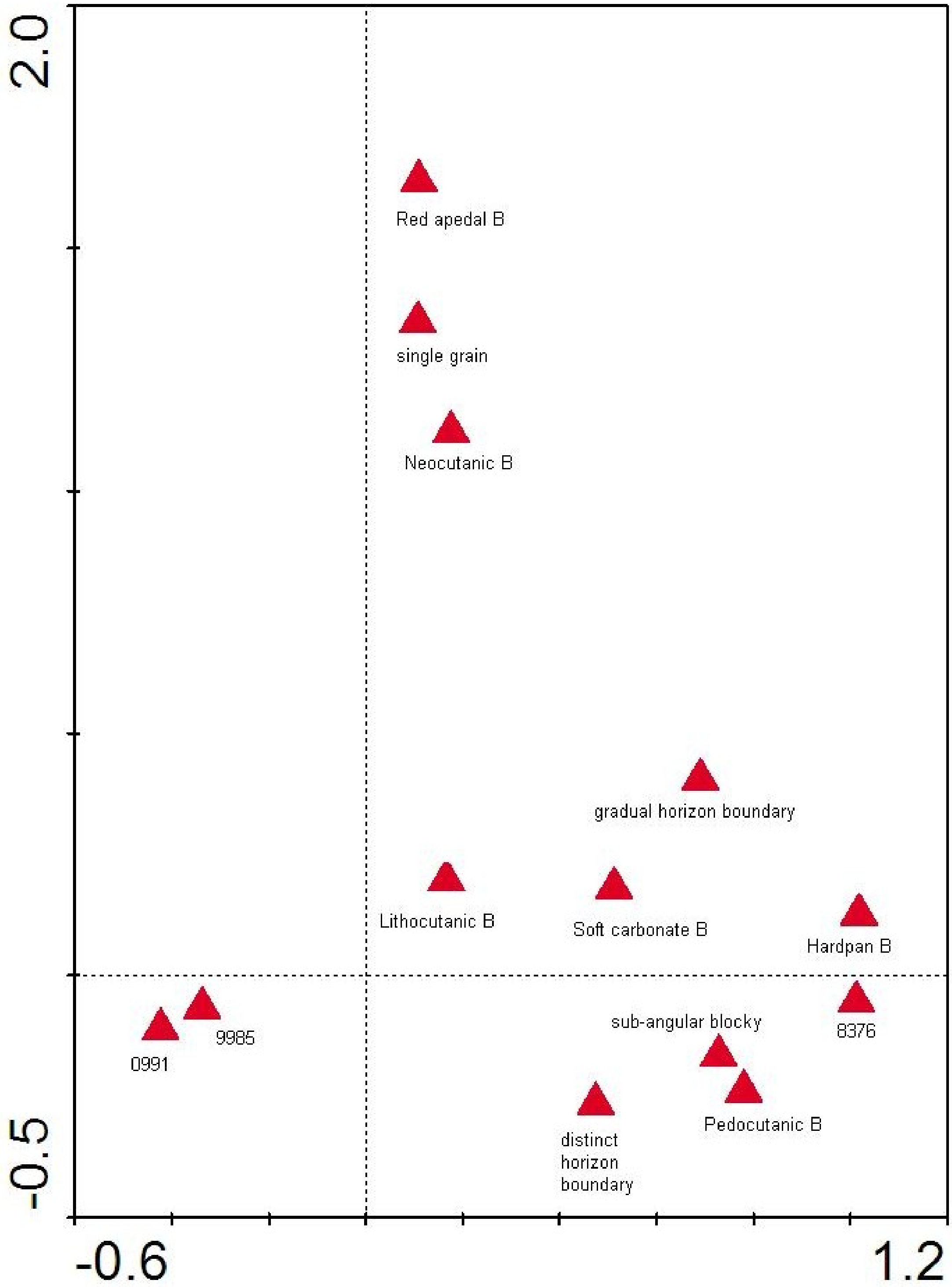


Figure 3.16. Standardised and centered PCA of the subsoil data collected for the 'decrease' in tree density sites. Eigenvalues: (1) 0.252 (2) 0.168. Total percentage represented by the first two axes is 42.0.

3.4. Discussion and conclusions

The PCA and univariate (Appendix 2) analysis conducted on the field soil properties show that many of the soil characteristics are similar across the Park, and are not specific to the observed vegetation changes. Soil structure can affect the behaviour of plants in many ways. However, the most prominent effect is on the physical form of the roots. This is particularly so in strongly structured soils, where root growth is negatively affected, thus greatly restricting their range. This has potentially detrimental consequences on the supply of water and nutrients to the plant and thus will influence the vegetation growth. Weakly structured or friable soils may also have adverse affects on plant growth, as their porous nature can suppress the contact that roots make with nutrients and water available in the soil (Passioura, 1991).

The sub-angular blocky, crumb, and granular structure classes found in many areas and associated with sites which show both a ‘change’ and ‘no change’ in vegetation are considered fine to moderate structures and could therefore not have a great influence on root growth, to the extent that their range is limited, and they are not able to acquire the available nutrients and water. The single-grain class found in many areas also appears to have a greater consistency than very friable soils and thus will increase the storage capacity of water and nutrients.

Although there is no distinct difference in soil structure between those sites where a change in vegetation growth has been recorded photographically and those which have not, there appears to be differences between those sites sampled in the Hluhluwe section as compared to those sites sampled in the iMfolozi section. The latter sites are associated more with the granular, crumb and single-grain structure in the topsoil i.e. sites 8168 and 7561 (Figures 3.7 and 3.11) as opposed to the Hluhluwe sites which have a greater occurrence of sub-angular blocky structure types i.e. sites 0898. This could be attributed to the wetter conditions experienced in the Hluhluwe section. Studies have found that soil structure is affected by the climate of the area and the higher the rainfall received the stronger the structure. The structure can also be associated with the organic matter content of the soil and therefore also the nutrient content (Lavee *et al.*, 1991, Passioura, 1991). Both these properties are influenced by changes in vegetation density. This therefore could be associated with the vegetation changes which have taken place in the Park. The increase in vegetation seen in many of the sites will increase the aggregate size and stability, and the soil organic matter content, through the more favourable soil conditions created which encourage microorganism activity and root growth (Sarah and Rodeh, 2004).

Two of the sites in the iMfolozi section have a higher percentage of sand particles as compared to other sites sampled in this area (Figure 3.13 shows site 8278 associated with single grain structure). This can be attributed to the close proximity of one of the sites, 8278, to the Black iMfolozi River. Flood events in this area can deposit sand on the banks of the river, which would increase the percentage of sand seen in the topsoil in the samples from this site. The other site, 8168 (Figures 3.7 and 3.8) which has a greater occurrence of samples with a sandy loam texture, granular and single grain structure and the occurrence of the Lithocutanic B horizon could be attributed to the parent material found in the area. The Ecca sediments that the site is situated on differ to the dolerite and basalt parent materials that underlie the other sites in iMfolozi and this could lead to a change in the soil texture found at this site compared to the others. The soil texture and its effect on the vegetation changes that have occurred will be discussed in greater detail in Chapter Four.

The horizon boundary can also have an influence on the vegetation growth in an area as it can impede root growth and inhibit the movement of water and nutrients down the profile (Seobi *et al*., 2005). This is particularly so in duplex soils, which consist of a contrasting soil texture between horizons, such as a topsoil consisting of a sandy or loamy soil texture and a subsoil with a high clay content (Blevins *et al*., 1996). The distinct horizon boundaries in the Hluhluwe, Corridor and iMfolozi sections, however, do not appear to have a great influence in determining the vegetation changes that have occurred. The duplex soil forms including Swartland, Valsrivier and Sepane will have an influence on vegetation growth through their clay textures in the subsoil increasing the storage capacity of water and cations available for plant uptake. However, other soil forms and families present in the same areas sampled will decrease the statistical significance of these duplex soils and their distinct horizon boundaries.

Colour, while not an influencing property in determining the vegetation growth patterns of an area does, however, aid in the field description of a soil. This is due to colour being an indicator of certain processes within the soil, such as leaching, hydration and the accumulation of organic matter. The darker colours may be related to the accumulation of certain minerals and organic matter and the brown to reddish colours found at many of the sites reflect good drainage and aeration within the profile. This is beneficial for the vegetation growth in the area as the infiltration of water and the circulation of air is an ongoing process in these profiles allowing for an increase in root growth.

The soil forms and families present in the various areas sampled are also not significantly different between sites where a 'change' or 'no change' has occurred in the vegetation patterns. However, their various unique characteristics do affect the vegetation growth in the areas they are found. This can be seen for example by comparing the 'no-change' site, 0894, and the 'slight increase' site, 0479, which both contain the Glenrosa soil form. The differences between these two sites is the depth of the profiles, which are considerably shallower at the 0894 site. The depth of the profile could be an influencing property in determining the vegetation growth in an area. The shallower soils appear to only support grassland while the deeper profiles associated with the 0479 site support a greater tree density. This could also be due to the storage capacity for water in the subsoil horizons (Scholes and Archer, 1997) which, if greater at the 0479 site, would allow for the increase in tree density observed.

The soil physical properties that were determined in the field in this study do appear to have an influence on the vegetation growth in the Hluhluwe iMfolozi Park. However, they are unlikely to be the driving force behind the vegetation changes recorded photographically. However, the impact that the individual properties have on the plants can help play a role in determining the class of vegetation in an area. This is mainly through the ability of the various soils to store water, organic matter and nutrients which are either sufficient to allow for the increase in tree density or to maintain a certain growth pattern at particular sites.

Chapter Four

The influence of soil properties measured in the laboratory on the vegetation of Hluhluwe iMfolozi Park

4.1. Introduction

Soil properties including fertility, pH and texture have an important influence on the presence of woody plants and the balance between grass and woody plant biomass in those ecosystems where they coexist (Dodd and Lauenroth, 1997). The nutrient content can also affect vegetation structure as individual nutrients can be limiting factors in the growth of particular vegetation types (Critchley *et al.*, 2002). These soil characteristics therefore need to be compared between sites where vegetation growth differs in order to understand if these properties are some of the causes of this change in vegetation growth.

This chapter examines the relative importance of soil properties analysed in the laboratory on the vegetation changes photographically recorded in Hluhluwe iMfolozi Park, to determine if any have an effect on the vegetation growth patterns of the area.

4.2. Materials and methods

4.2.1. Preparation of samples

Due to the large number of soil samples collected from the fourteen sites sampled, one transect per site was chosen for laboratory analysis, which represented the greatest proportion of soil types found at that site. Therefore not all samples collected were analysed and the number of samples analysed differed between sites and depended on how many points the selected transect from each site contained. The samples which were collected by horizons were air-dried and ground to pass through a 2mm sieve, before being analysed.

4.2.2. Laboratory analysis

The pH was measured in distilled water and 1M KCl. A soil:solution ratio of 1:2.5 was used (10g of soil and 25ml of solution), and the pH measured with a standard glass electrode on a Radiometer PHM210 pH meter. The exchangeable acidity was analysed after displacing the exchangeable and solution acidity using 1M KCl and then determined by titration with 0.01M NaOH.

Organic carbon was determined using the method of Walkley (1947). Phosphorus was extracted with ammonium bicarbonate solution (AMBIC) (Hunter, 1974; Van der Merwe *et al*., 1984) and determined colorimetrically through the absorbance being read on a Varian Cary 1E UV-Visible spectrophotometer set at 670nm and the concentration of phosphate read off a standard curve. The cation exchange capacity was analysed using the method of Hughes and Girdlestone (1994). The soil was saturated with Sr^{2+} with subsequent replacement with NH_4^+. Calcium, magnesium and strontium were determined by atomic absorption spectrophotometry and potassium and sodium by flame emission spectrometry on a Varian SpectrAA 210. The particle size distribution was determined using the pipette method (Gee and Bauder, 1986).

4.2.3. Statistical analysis

The results of the samples analysed were separated into the five vegetation change categories. The topsoil and subsoil were also separated out for each area, as these generally have distinct soil properties and thus affect vegetation growth differently.

Statistical models were determined using Canoco for Windows 4.5 and run using a principal component analysis (PCA). The pH, exchangeable acidity, texture, nutrients and organic carbon for the top and subsoil were included in the models and were analysed against the site category. This allows for one to see which soil properties were associated with the various site categories.

The results of the samples analysed were also averaged and separated into the various vegetation classes that are being studied. These are shown graphically (Appendix 6) for the pH, nutrient and texture analysis.

4.3. Results

4.3.1. Principal Component Analysis

The PCA analyses of the sites (Figures 4.1 to 4.10) show the soil characteristics that are most associated with a particular site. The ‘no change’ in vegetation site 0898 is associated with an increase in organic carbon and K for both the top and subsoils while 8168 is more associated with the various fractions of sand particles for both the top and subsoil (Figure 4.1 and 4.2). The site 0894 appears to be linked to P content and the pH of the soil more than the other ‘no change’ sites. Site 9570 is linked to the various cations including Na, Mg and Ca particularly in the subsoil (Figure 4.2).

The ‘increase’ in vegetation site 0479 is associated with the fine sand texture class in the topsoil (Figure 4.3) as well as the pH of the subsoil (Figure 4.4). Site 9782 is linked with the coarse sand texture class, particularly in the subsoil. The nutrient content (especially Mg and P) is associated with site 9579 in the subsoil while in the topsoil the site is associated almost exclusively with P (Figure 4.5). Ca, however, is more related to site 7561 in the subsoil (Figure 4.6). Site 0994 is associated with clay and organic carbon in the topsoil and with exchangeable acidity and silt content in the subsoil (Figure 4.5 and 4.6).

The ‘slight decrease’ in vegetation site 8278 is linked to the pH and fine sand content in both top and subsoil (Figures 4.7 and 4.8). Site 9574 is associated with the coarse sand content and the calcium and organic carbon content in the soil (Figure 4.8). The ‘decrease’ site 8376 is related to nutrient availability especially Na and Ca as well as the clay content and pH for both the top and subsoil (Figures 4.9 and 4.10). 0991 is associated with the medium sand texture class and exchangeable acidity, especially with the subsoil and site 9985 is linked to the coarse sand texture class for the topsoil (Figure 4.9) and the organic carbon and K content in both top and subsoil (Figure 4.10).

4.3.2. pH and exchangeable acidity

The pH for both H_2O and KCl of the soil, in all areas, fell within a wide range of 4.33 – 7.62. The pH is influenced by the rainfall in the area and thus sites sampled in the Hluhluwe section are more acidic than those sampled in the Corridor and iMfolozi sections. The topsoils had a higher pH for all the samples and were in the range between 5 and 7. The exchangeable acidity measurements were low (from 0.0 – 0.926 $cmol_c\ kg^{-1}$). They were, however, higher in the subsoil as opposed to the topsoil (Appendix 5).

4.3.3. Nutrients

The nutrient contents of the soils did not appear to vary greatly between the different areas. The content of all the cations measured are greater in the topsoil as compared to the subsoil samples. This is to be expected as the topsoil, which has a higher percentage of organic matter than the subsoil, will hold more cations, thus making them more available for plant uptake. The calcium and magnesium are greater for all sites as compared to the potassium and sodium. For example 8.81 $cmol^+$/Kg and 5.73 $cmol^+$/Kg respectively compared to 0.72 $cmol^+$/Kg and 0.79 $cmol^+$/Kg respectively. The sodium content increases between the top and subsoil samples obtained for all sites. The cations exchange capacity (CEC) of all the sites varies slightly and many of the sites have a low CEC (i.e. 4.28 $cmol^+$/Kg). The organic carbon percentage and AMBIC phosphorus varied across the different sites but were higher in the topsoil (i.e. 4.21%) as compared to the subsoil (1.11%) for all samples (Appendix 6). No distinct association was found between any nutrients tested in the laboratory and the various vegetation changes.

4.3.4 Texture

The clay percentage increases between the top (i.e. 50.42%) and subsoils (i.e. 61.86%) for all the sites sampled. The silt and various fractions of sand percentages vary across all sites and are lower than the clay percentage in all sites except the A horizon of the ‘slight increase’ sites. The ‘no-change’, and ‘increase’ sites have a higher percentage of clay as compared to the silt and sand fraction for both the A and B horizon. The ‘slight increase’ sites have a higher percentage of sand in the A and B horizon, the ‘slight decrease’ sites have a more equal percentage between the sand, silt and clay fractions in the A horizon and a greater percentage of clay in the B horizon. The decrease sites have a greater percentage of clay and silt in the A and B horizon. Appendix 7 shows means of the clay, sand and silt fraction for all sites, and the clay fraction is greatest for the A and B horizon, across the different vegetation change classes.

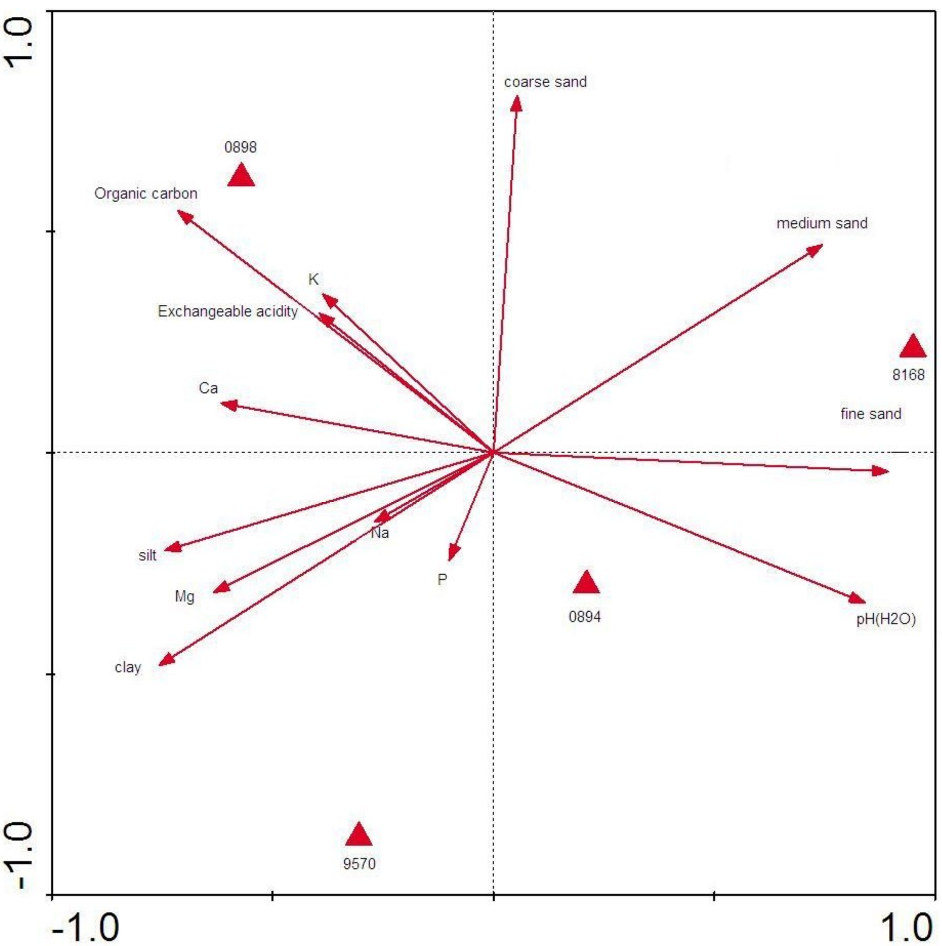


Figure 4.1. PCA of standardised and centered data of the topsoil data analysed in the laboratory for the 'no-change' in vegetation density sites. Eigenvalue: (1) 0.331 (2) 0.173. Total percentage represented by the first two axes is 50.4.

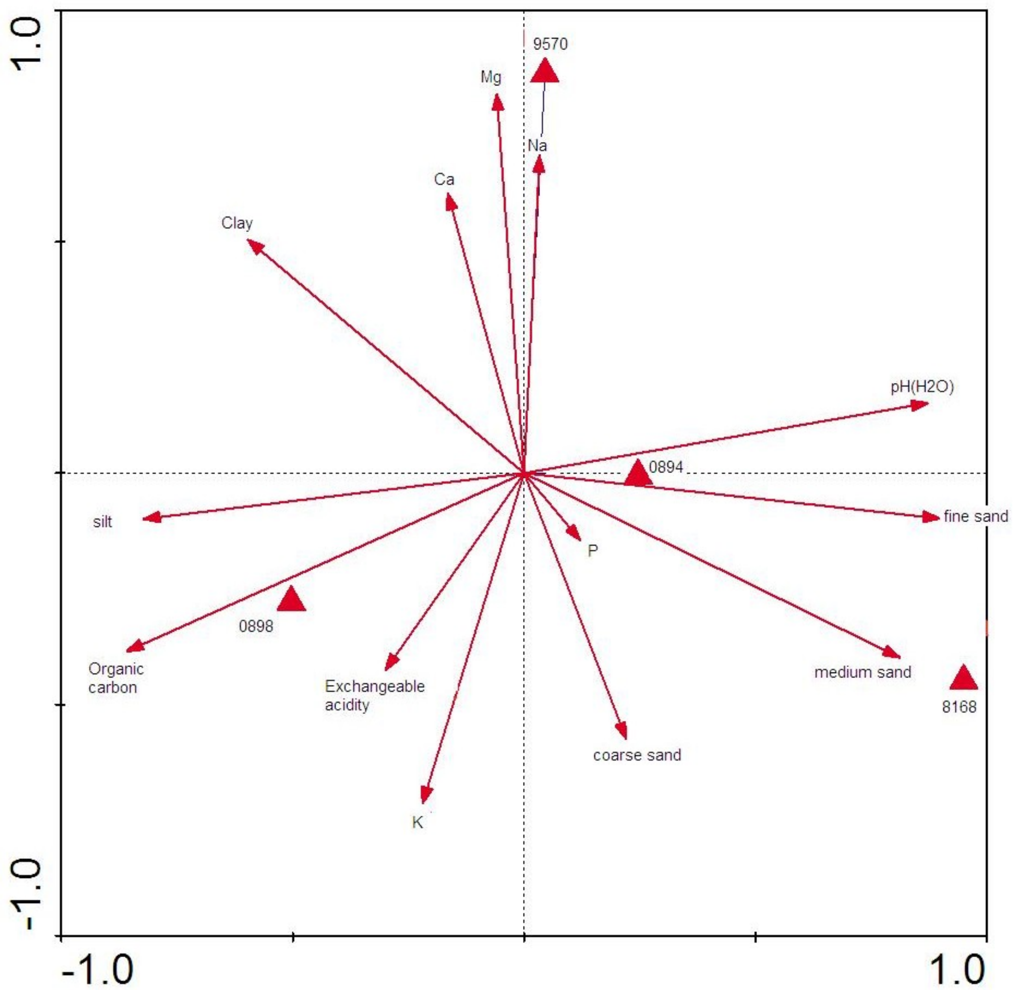


Figure 4.2. PCA of standardised and centered data of the subsoil data analysed in the laboratory for the 'no-change' in vegetation density sites. Eigenvalue: (1) 0.328 (2) 0.250 Total percentage represented by the first two axes is 57.8.

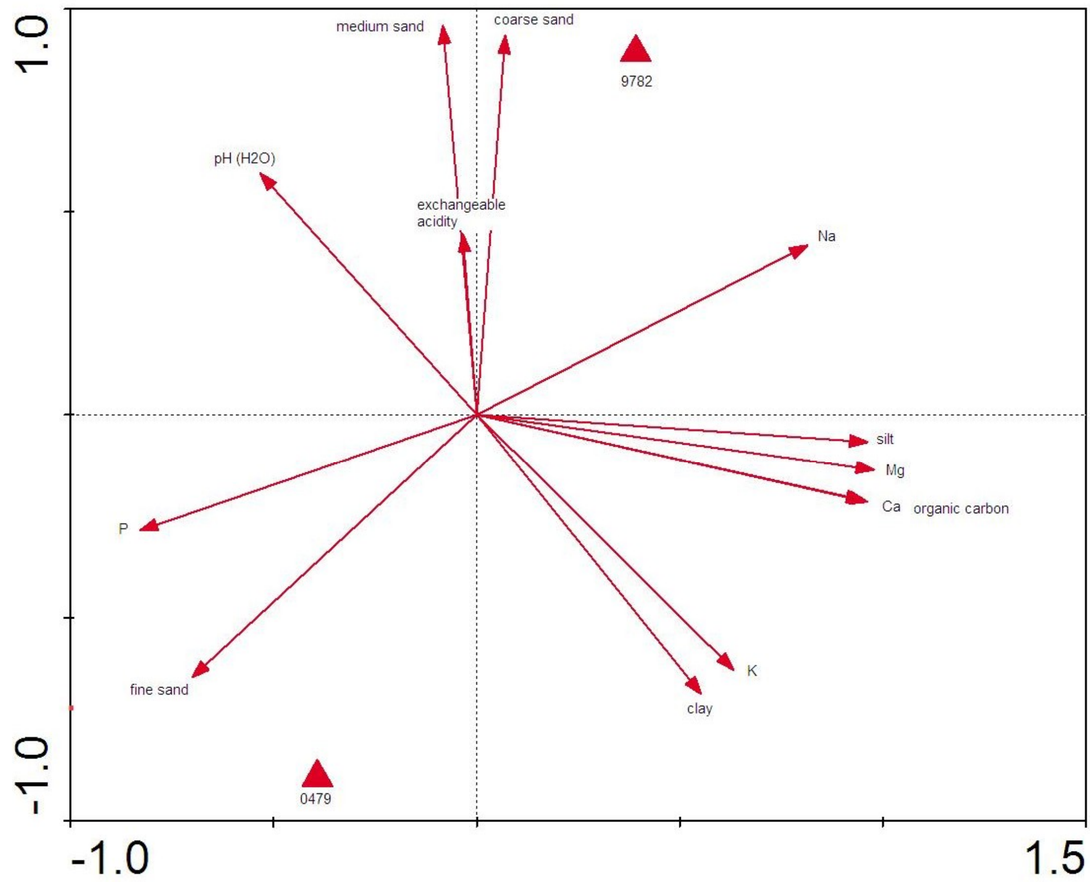


Figure 4.3. PCA of standardised and centered data of the topsoil data analysed in the laboratory for the 'slight increase' in tree density sites. Eigenvalue: (1) 0.458 (2) 0.373 Total percentage represented by the first two axes is 85.1.

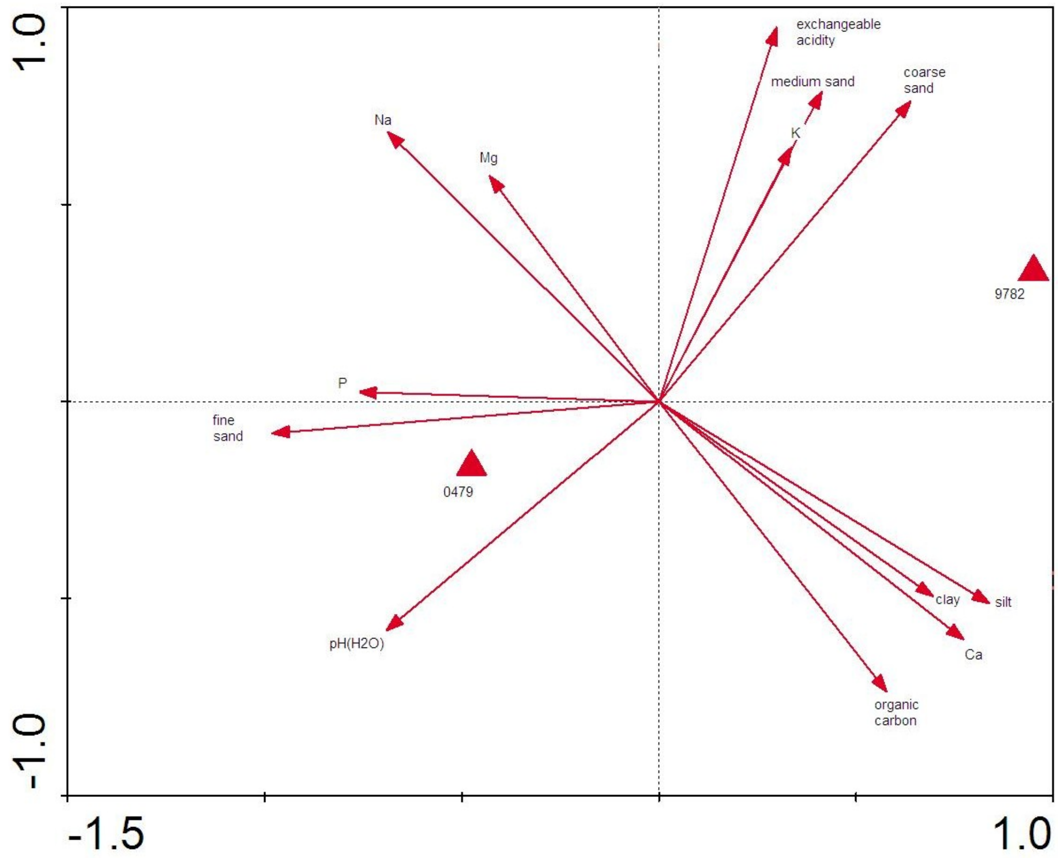


Figure 4.4. PCA of standardised and centered data of the subsoil data analysed in the laboratory for the ‘slight increase’ in tree density sites. Eigenvalue: (1) 0.489 (2) 0.352 Total percentage represented by the first two axes is 84.1.

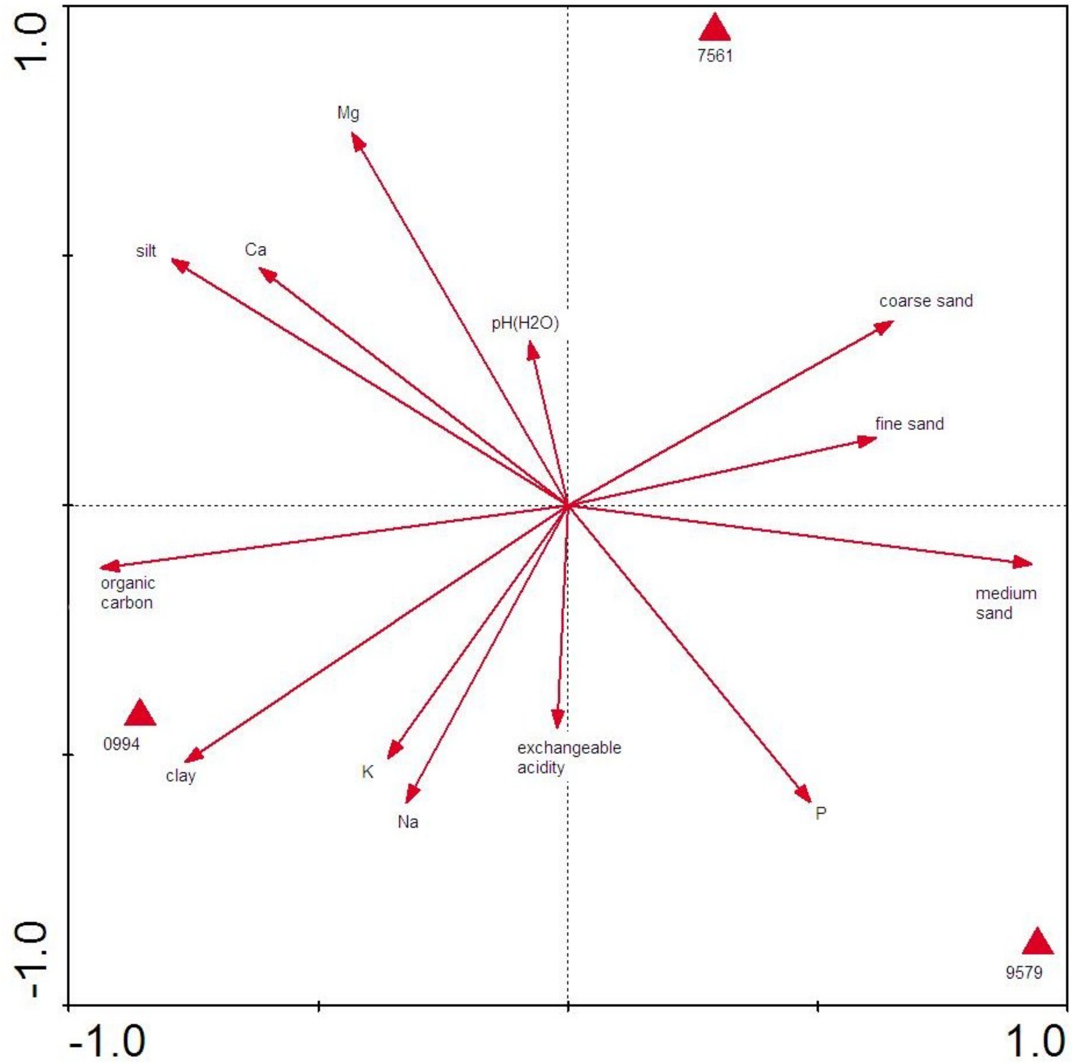


Figure 4.5. PCA of standardised and centered data of the topsoil data analysed in the laboratory for the ‘increase’ in tree density sites. Eigenvalue: (1) 0.367 (2) 0.250 Total percentage represented by the first two axes is 61.7.

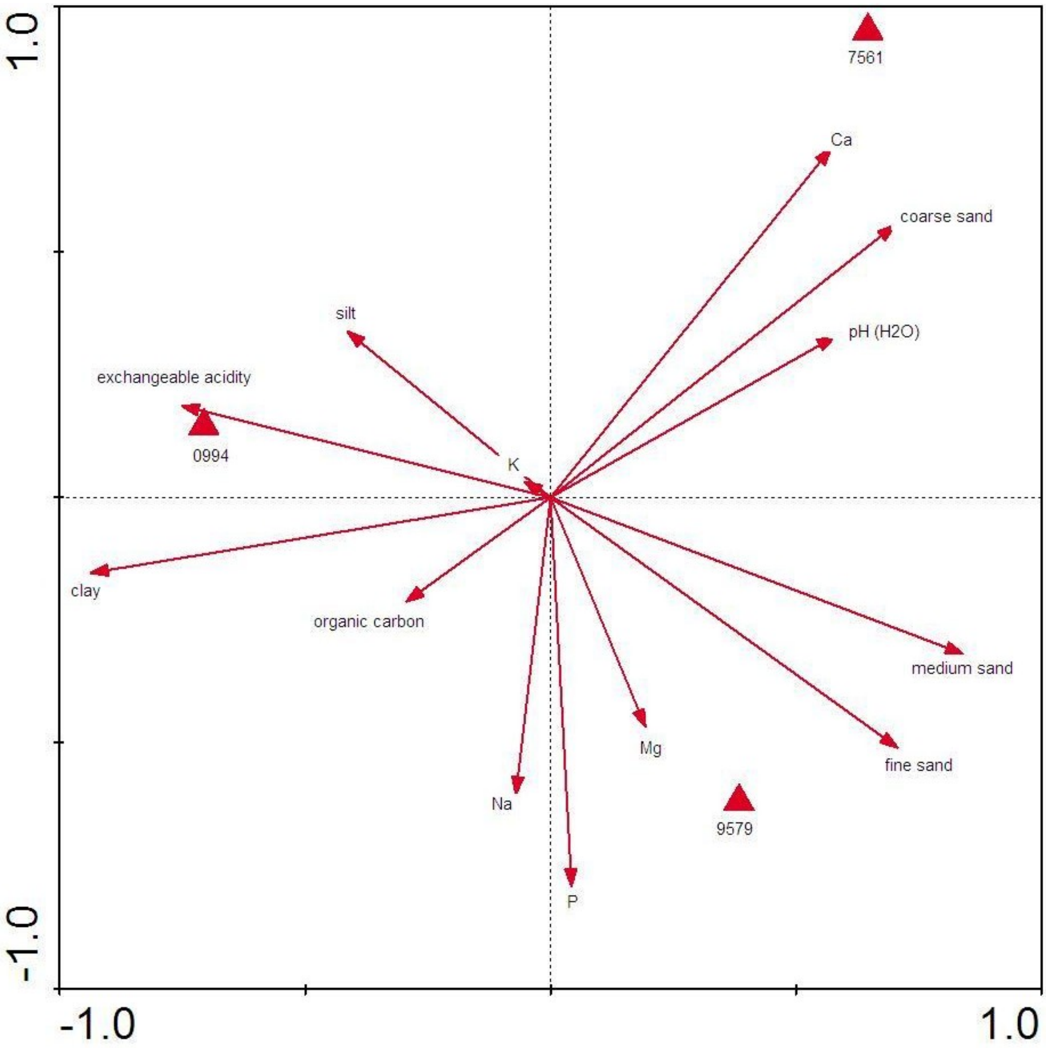


Figure 4.6. PCA of standardised and centered data of the subsoil data analysed in the laboratory for the 'increase' in tree density sites. Eigenvalue: (1) 0.348 (2) 0.254 Total percentage represented by the first two axes is 60.2

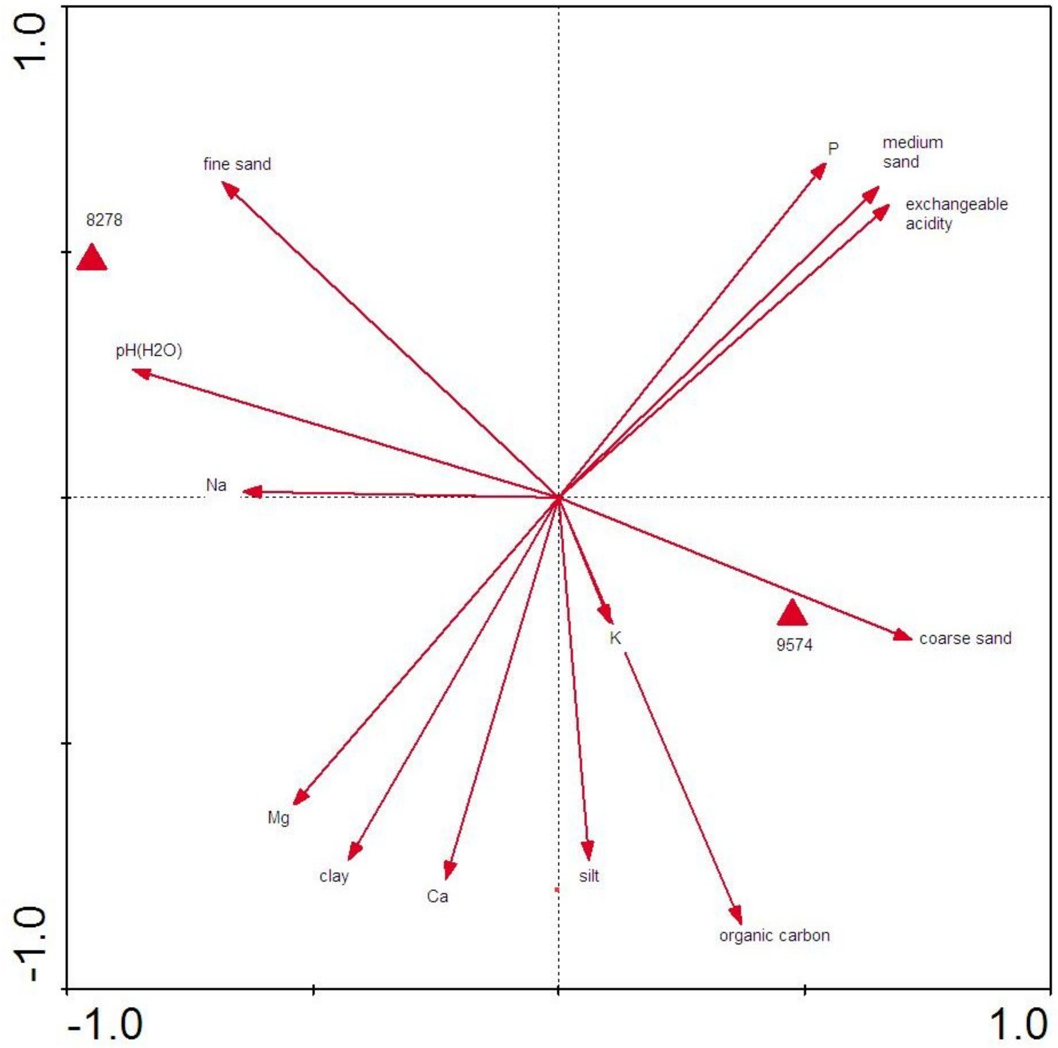


Figure 4.7. PCA of standardised and centered data of the topsoil data analysed in the laboratory for the 'slight decrease' in tree density sites. Eigenvalue: (1) 0.364 (2) 0.337 Total percentage represented by the first two axes is 70.1.

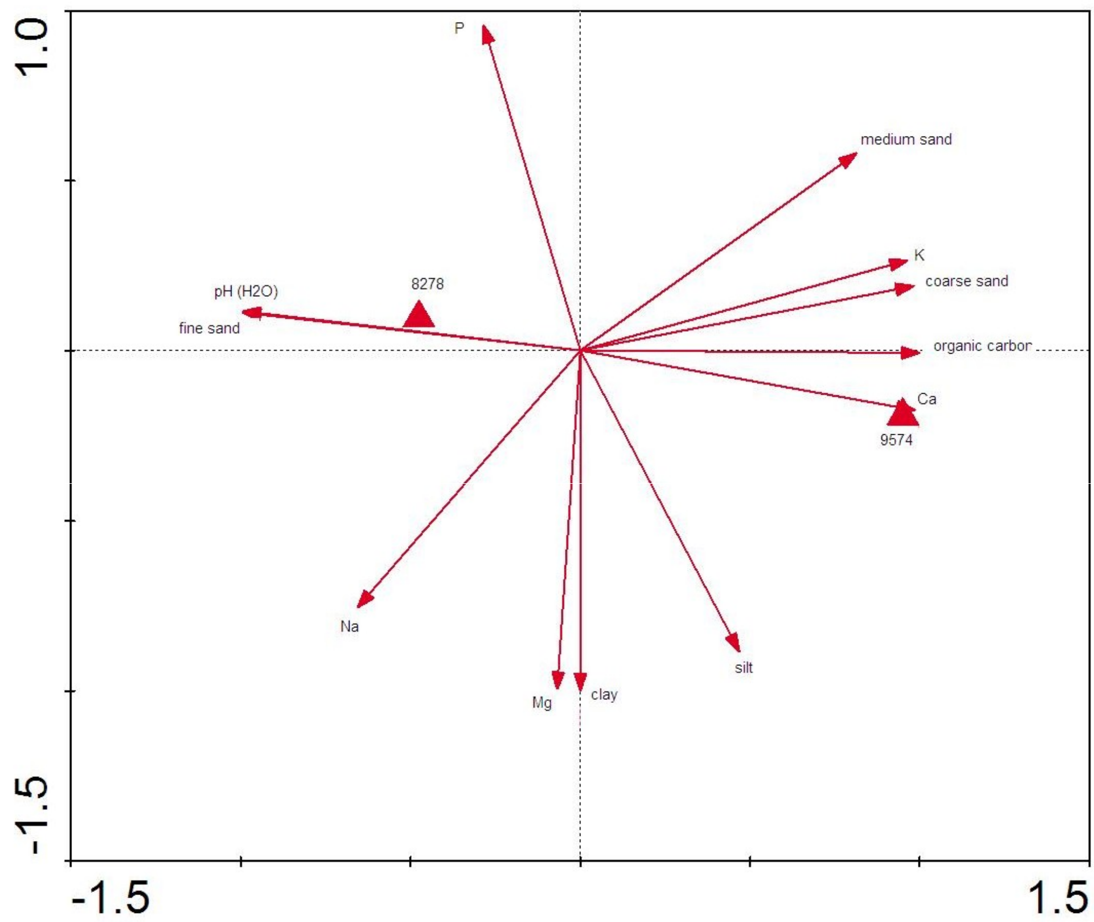


Figure 4.8. PCA of standardised and centered data of the subsoil data analysed in the laboratory for the 'slight decrease' in tree density sites. Eigenvalue: (1) 0.654 (2) 0.346 Total percentage represented by the first two axes is 100.0.

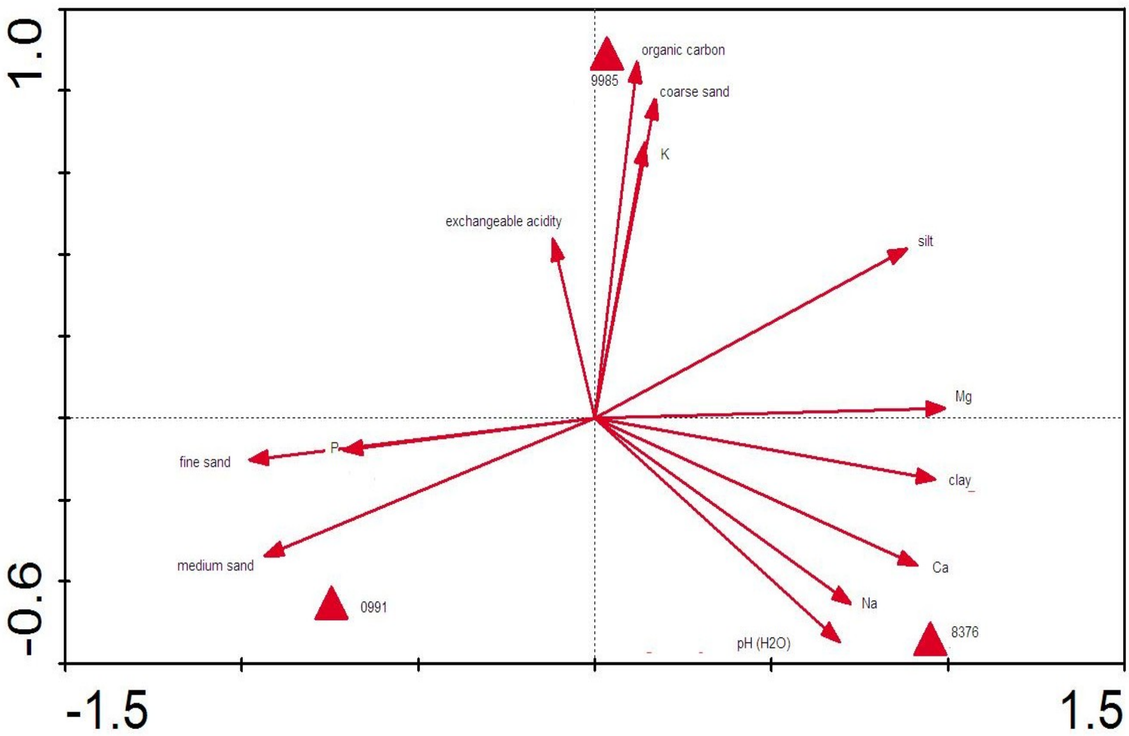


Figure 4.9. PCA PCA of standardised and centred data of the topsoil data analysed in the laboratory for the 'decrease' in tree density sites. Eigenvalue: (1) 0.522 (2) 0.277 Total percentage represented by the first two axes is 79.8.

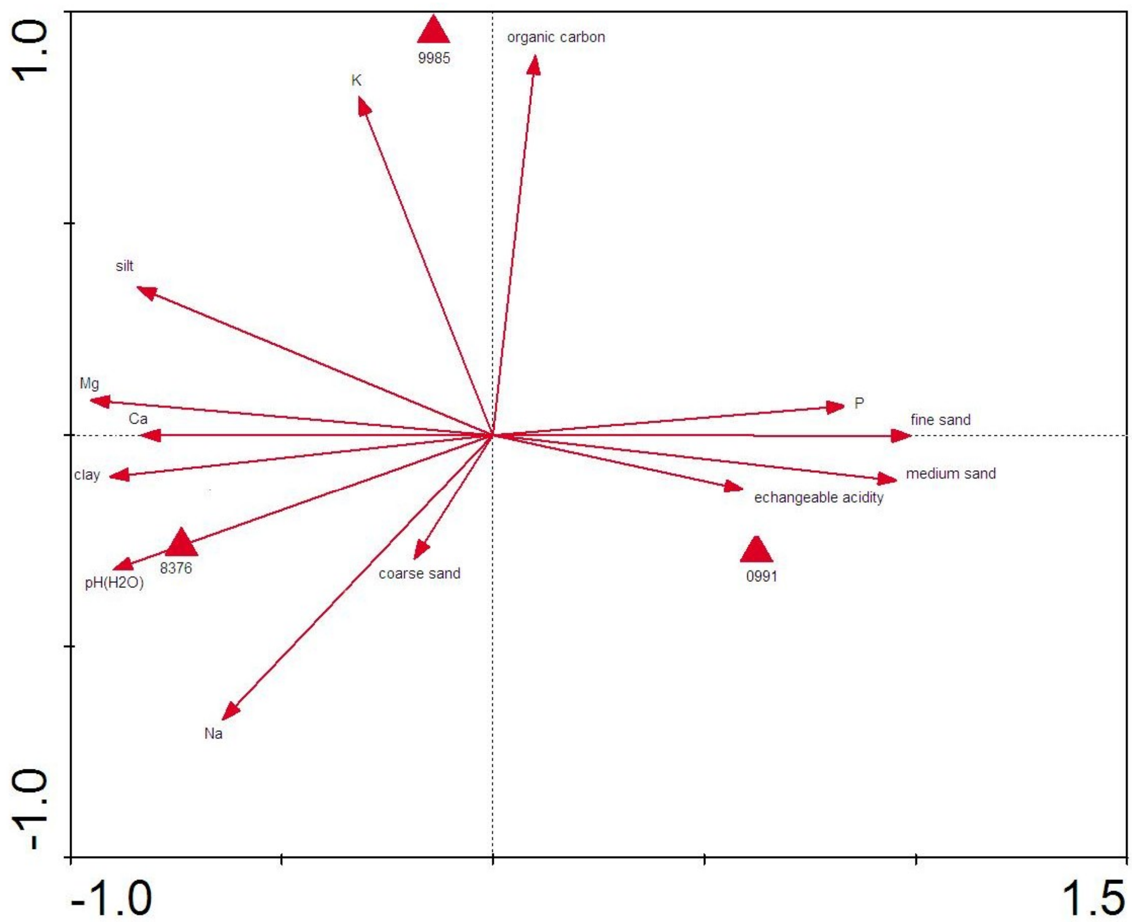


Figure 4.10. PCA of standardised and centered data of the subsoil data analysed in the laboratory for the 'decrease' in tree density sites. Eigenvalue: (1) 0.557 (2) 0.197 Total percentage represented by the first two axes is 75.4.

4.3. Discussion and conclusions

One of the most influential soil factors affecting the vegetation structure is texture as it directly influences the storage capacity of the soil for water, air and mineral nutrients (Worrall, 1960). A number of authors have suggested that vegetation patterns and the changes in these are attributed to a variation in texture and the soil parent material (Fraser *et al*., 1987; Dodd and Lauenroth, 1997; HilleRisLambers *et al*., 2001). Soil texture appears to control many features in a savanna ecosystem as it affects not only the availability of water but is also a key determinant of soil organic matter content and the availability of nutrients for plant uptake (Hook and Burke, 2000). However, from the present data there does not appear to be any links between particular soil texture classes and a change in vegetation patterns. An increase in clay creates soils with a finer texture which can allow for the greater storage of water, nutrients and organic matter (Knoop and Walker, 1985; Passioura, 1991; Hook and Burke, 2000). A higher percentage of silt plus clay in a soil also promotes the accumulation of soil organic matter and nutrients by aggregate formation and adsorption onto mineral surfaces (Hassink, 1996). Certain sites which are associated with clay content (site 0994) as shown in the PCA analysis are categorised as having an increase in vegetation. However, this is also true for sites where a decrease in tree density has occurred, i.e. site 8376. However site 8376 appears to be more associated with Na, Ca and the pH of the soil (Figure 4.9) and these are most certainly related to the clay content and to each other. Changes to soil texture due to weathering can take a long time and so are unlikely to have influenced the vegetation dynamics over the period that this study is investigating. Some of the sites sampled in the Corridor section (including 9985, 9782, 9579 and 9574) appear to have more equal percentages of silt and clay. This increase in the percentage of silt in the Corridor section can be attributed to the parent material found in this area. The main parent materials associated with these sites are the Ecca Group Vryheid formation deposits which underlie extensive areas of the Corridor.

The coarse-over-fine texture contrast between horizons which is common in soils throughout the sites sampled and across a variety of environmental settings, can form in response to a combination of factors. These include the movement of the fine clay particles into the subsoil as water infiltrates down the profile, or the translocation of clay particles to the surface through bioturbation and then their subsequent removal through erosion. Clay that is retained in the subsoil will therefore increase the percentage. These theories help explain the coarse topsoils and heavier textured subsoils seen in many of the sites sampled. However, they do not explain why a particular vegetation change has occurred in an area as they are not a factor of any one particular set of processes or controls (Paton *et al*., 1995; Phillips, 2004).

One model proposed by Walter (1971) and Walker and Noy-Meir (1982) has been used to describe how trees can encroach into an area. This model demonstrates that under savanna conditions, trees are the superior competitors for water in the subsoil due to the infiltration of water into the lower horizons and their roots allow them to access this water. Variations to this model have been proposed, however, and woody plants have been shown to obtain their water from both the top and subsoils (Breshears and Barnes, 1999). The higher percentage of clay in the subsoil horizons does, however, allow woody plants to obtain the water needed to encroach into an area. Therefore a high percentage of clay in soils of an area could reinforce other environmental changes such as in herbivory movement and fire patterns and this could lead to an increase in tree density.

The texture of the soil, as stated earlier, also affects the availability of nutrients and presence of organic matter. The organic matter contributes to the fertility and structure of the soils and is thus an important property in determining the vegetation growth patterns of an area (Kelly *et al*., 1996). The soil texture directly influences the organic matter accumulation, especially in the topsoil, and thus can affect the vegetation growth patterns in an area (Breshears and Barnes, 1999). The percentage of clay and silt found in the soils in Hluhluwe iMfolozi Park can have an influence on the accumulation of nutrients in the soil and therefore affect the type of vegetation growing and the changes which occur in this area. This is due to changes in the quantity of organic matter and nutrients being relatively rapid and can thus have an influence on the vegetation growth within the time frame of this project.

The availability of nutrients, such as phosphorus and exchangeable cations, strongly influence the rate at which vegetation grows and thus can be a determinant of the structure and composition of the vegetation types in an area (Walker and Langridge, 1997; Hagos and Smit, 2004). The phosphorus content has been shown to often be the limiting factor across a wide range of soil types, as shown in various studies conducted in different countries, in determining the vegetation growth patterns of an area and how these change (Kirkham *et al*., 1996; Janssens *et al*., 1998). The vegetation patterns can also be influenced by the variation in nutrient availability and the limitations this can cause between species, as this can be one of the driving factors for species richness in an area (Koerselman and Meuleman, 1996). Several studies have shown this, especially with regard to an increase in phosphorus and some cations such as potassium and calcium which could decrease the species richness in an area (Janssens *et al*., 1998; Hook and Burke, 2000; Critchley *et al*., 2002). The nutrients in the sampled areas could result in an increase in bush encroachment, and thus decrease the species richness in certain areas of the Park over the time period of this study. The sites sampled in the Hluhluwe and Corridor sections have, for the most part, been classified as having an increase in tree density over the period studied. This is true even for those sites classified as ‘no change’ in vegetation sites, as a small increase in the percentage of trees (<4%) was observed. However, there does not appear to be any relationship between any specific nutrients and change in vegetation type across the sites sampled. This is also shown in the PCA analysis where both an increase and decrease in tree density is associated with particular nutrients. However, the quantity of these nutrients differs between sites and this may be an influencing factor in the growth of particular vegetation patterns.

The differences seen in the nutrient content of many soils can be explained by the parent material, which determines the original supply of nutrients that are released by weathering and thus influences the balance between nutrient loss and retention (Anderson, 1998). The input of nutrients released by weathering depends on the stability of the minerals in which they are contained. Most of the sites are situated on sedimentary rocks. These, as parent materials, have been shown to develop a greater percentage of soils with a higher iron and sodium content ((Bühmann, 1994). There are also sites situated on basalt and dolerite and these parent materials have been shown to produce soils with a greater calcium and phosphorus content (Ranov and Yaroshevsky, 1972). In the samples analysed particular nutrient contents do not appear to increase or decrease with regard to the parent material the site is situated on. This could be due to variations in the fertility of soils within the landscape. Therefore to categorise soils from the same parent material as having either a high or low nutrient status is a generalisation (Scholes, 1990). The nutrient content of a soil is more specific to the area the soil is found in, the various factors of the soil’s formation and the continued interrelationships between these.

The pH of soils is also an important consideration in determining which soil properties influence vegetation patterns in a particular area. The pH affects the chemical status of a soil and thus also the availability of various elements for plant uptake (Roem and Berendse, 2000). Rainfall affects soil pH through the leaching of base cations from the soil, and their subsequent replacement by acidic cations such as aluminum (Smith *et al*., 1994). Therefore soils formed under higher rainfall conditions experienced in Hluhluwe were more acidic than those formed in the drier areas of the Corridor and iMfolozi sections.

The change in tree density at the sites sampled in Hluhluwe iMfolozi Park leads to various interactions between herbaceous vegetation and woody plants in the different areas (Belsky *et al*., 1989). Generally an increase in woody plant cover, as seen at many of the sites sampled, results in a grass production decline in that area. Trees, however, do not only affect the above-ground environment, but can also alter many soil properties in their surroundings (Scholes and Archer, 1997). Many reports have found that trees and grasses can improve the structure of soils through the binding of particles with their roots and enhance the nutrient pools of soil nutrients and their fluxes (Belsky *et al*., 1989; Frost and Edinger, 1991). The nutrient enrichment of soils can, however, depend on the species of tree present, the litter inputs and the decomposition rates as compared to the herbaceous vegetation (Scholes and Archer, 1997). The improvement in the structure of soils can influence soil water and this could lead to trees out-competing the herbaceous layer and therefore increasing in density. This, however, was not statistically proven in the sites sampled in HIP.

Although the nutrient availability and texture of the soil could be of importance in influencing the vegetation growth patterns of an area, there are no clear links between particular texture classes or nutrients and a change in vegetation type in Hluhluwe iMfolozi Park over the period of this study. Due to the availability of water being one of the key factors that influences the balance between woody and herbaceous plants (Breshears and Barnes, 1999), the texture and structure of the soil and thus the water holding capacity could play a role in determining the vegetation types present at a site even though this was not shown statistically. Structure of a soil can change in a relatively short period of time and thus could have an effect on the type of vegetation growth in a particular area. This is also true for the nutrient content of a soil which can affect the type of species found at a site

Chapter Five

General conclusions

The use of fixed-point photographs in this study provided a 24 year record of the changes in the vegetation growth that have occurred in Hluhluwe iMfolozi Park, whether this involved an increase or decrease in tree density in an area. However, they did not allow for the factors, which caused these changes to be identified. This provided a chance to determine if soil properties found in these areas play a role in affecting the vegetation patterns. The soil properties recorded in the field and determined from laboratory analysis in this study have all been shown to have an effect on the balance between woody and herbaceous vegetation in other studies, and were thus expected to have an influence on the plant growth at the sites sampled.

Relationships between specific soil characteristics measured in either the field or laboratory and the vegetation patterns recorded were not found. However, these soil properties could have an effect on the plant growth in particular areas of the Park. One of the main effects is through the soil structure, as an increase in the water holding capacity of more strongly structured soils as found throughout the Park, can allow for an increase in plant density in an area. The structure of the soil does not, however, appear to be strong enough to inhibit root growth in the Park and limit the range in which plants can take up available nutrients and water, although this was not investigated in this study. The varied soil forms found throughout the Park were not unique to specific vegetation patterns or sites which had certain changes in the vegetation compositions seen. This is due to the soil forms being a function of the varied soil forming factors which occur throughout the Park, including the climate, parent material and topography. However, the various specific properties, such as depth, texture, fertility and organic matter content, of each soil form at each site will likely have an effect on the plant growth in that area as each property is interrelated and influenced by others. This is especially so for the structure of the soil, the fertility and the organic matter content, as strongly structured soils can improve the fertility status, and *vice versa*. With an increase in soil structure, the vegetation of an area can increase, thus improving the fertility and organic matter content. With an increase in the fertility and organic matter content, the greater density of vegetation can also improve the structure through the binding of soil particles to the roots.

These factors, however, do not appear to be the influencing reasons behind the changes in vegetation patterns recorded throughout the Park.

The pH of the soils sampled were within a wide range, owing probably to the different climatic conditions experienced across the Park. The exchangeable acidity values were generally low, and the samples from the sites in the Hluhluwe section were slightly more acidic due to the higher rainfall conditions experienced there.

The texture of the soils varied throughout the Park. The percentage of clay in the soil has an effect on the vegetation dynamics of an area and this is most likely due to the greater water and nutrient storage capacity in most clay soils compared to sandier soils. The clay texture, which also has an influence on the organic matter accumulation in a soil, affects vegetation densities providing more available nutrients for plant uptake and having an effect on the nutrient cycles. However, the clay percentage is unlikely to have changed in the time period of this study, except in areas were flooding has occurred, therefore it is unlikely to be a driving factor in the vegetation changes recorded. The nutrient status can also have an influence on the vegetation growth of an area. All nutrients analysed varied throughout the sites sampled but an apparent relationship between specific nutrients and vegetation changes was not found. The nutrient status of a soil has been shown, however, to have an effect on the plant growth and the balance between herbaceous and woody vegetation. This could be due to vegetation composition being influenced by variation in the different nutrients which are available for plant uptake, as these can be the driving factor in determining the species richness in an area.

From this study it seems as though the recent changes in the vegetation patterns observed in HIP are more associated with other environmental factors, including fire and the influence that grazers and browsers have on the vegetation. Although the soil properties analysed, excluding texture, are not constant properties and can change relatively rapidly, within the time period of this study they do not appear to be driving factors in determining the vegetation changes recorded in the fixed-point photographs. It is therefore more likely that the vegetation changes shown in the photographs over the relatively short time period of this study would have been enhanced by other factors experienced in the Park. The decrease in tree density patterns seen at the sites could have most likely been due to the effects of fire on the tree density, and a slow recovery rate experienced in these areas. The soil characteristics in these areas could, however, have an influence on the recovery rate, through the availability of water and nutrients, as seen with the low cation exchange capacity of the samples analysed. The sites categorised as having an increase in vegetation, are not unique to the specific areas of the Park sampled but occur throughout the area. This bush encroachment is again most likely due to a combination of factors of which soil properties are but one.

The aim of this study was to highlight any soil characteristics which could potentially explain the changes which are occurring in the vegetation communities in HIP. Although the nutrient status, texture, pH and structure of the soil are important determinants of the type of vegetation found in an area, the soil properties analysed here are not likely to be the only influence on the vegetation changes seen. The changes in the vegetation dynamics of Hluhluwe iMfolozi Park are most likely due to a combination of environmental and human factors, which are all interrelated, and which allow for the ever-changing vegetation communities seen.

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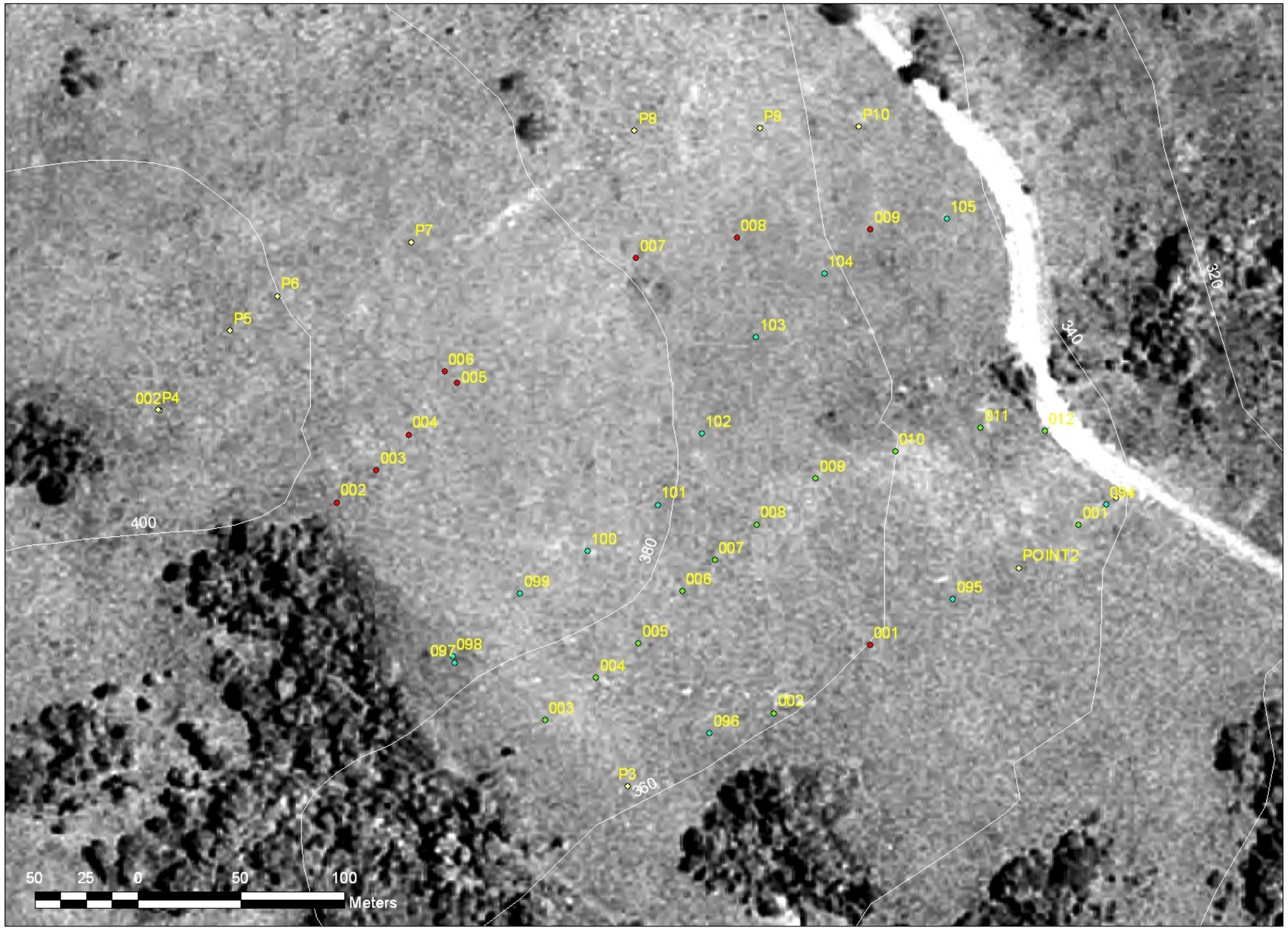
Appendices

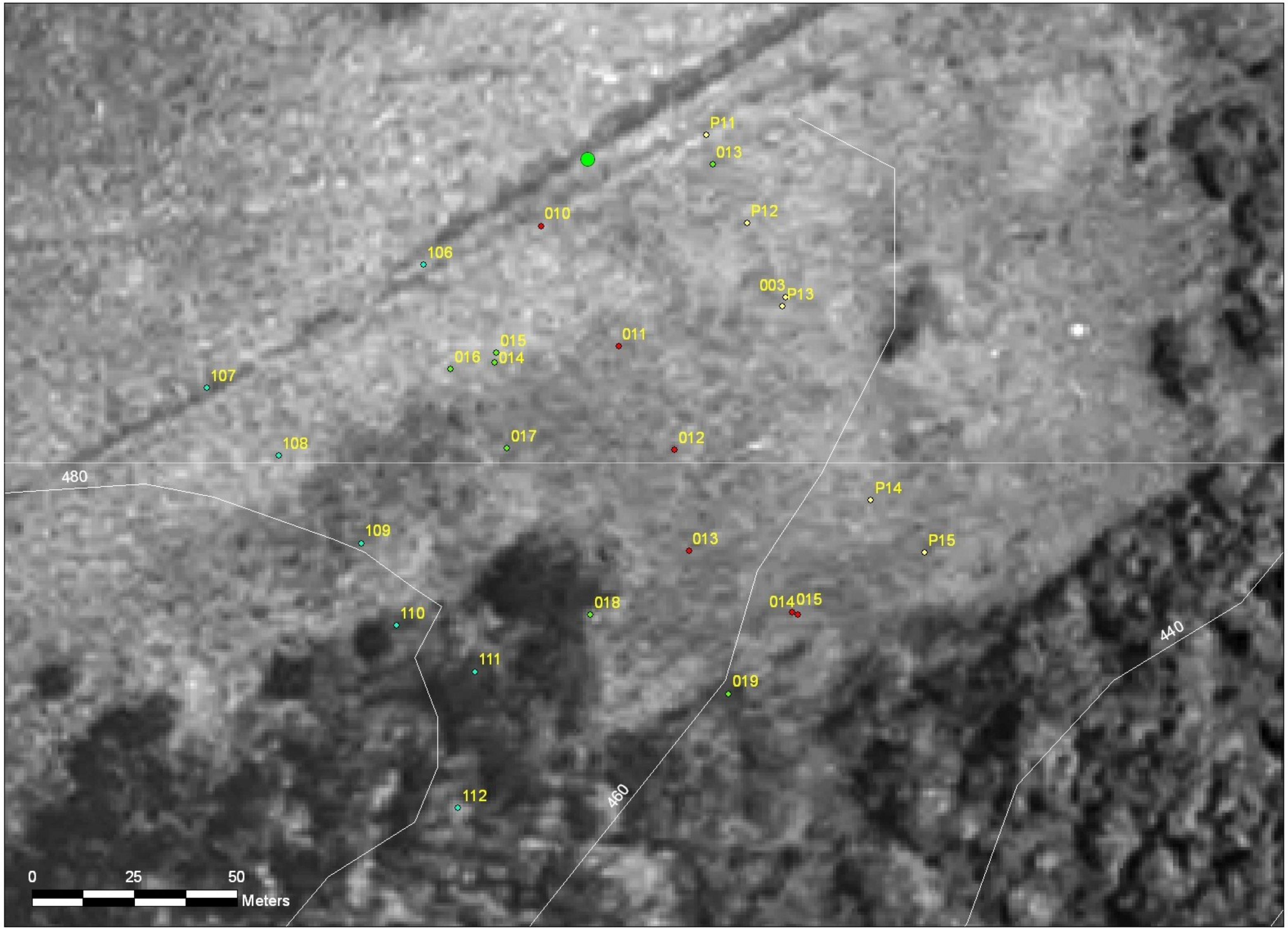
Appendix 1. Aerial photographs of the transects completed for the various sites

Appendix 1.1. Aerial photographs of the 'no change' sites showing the transects completed

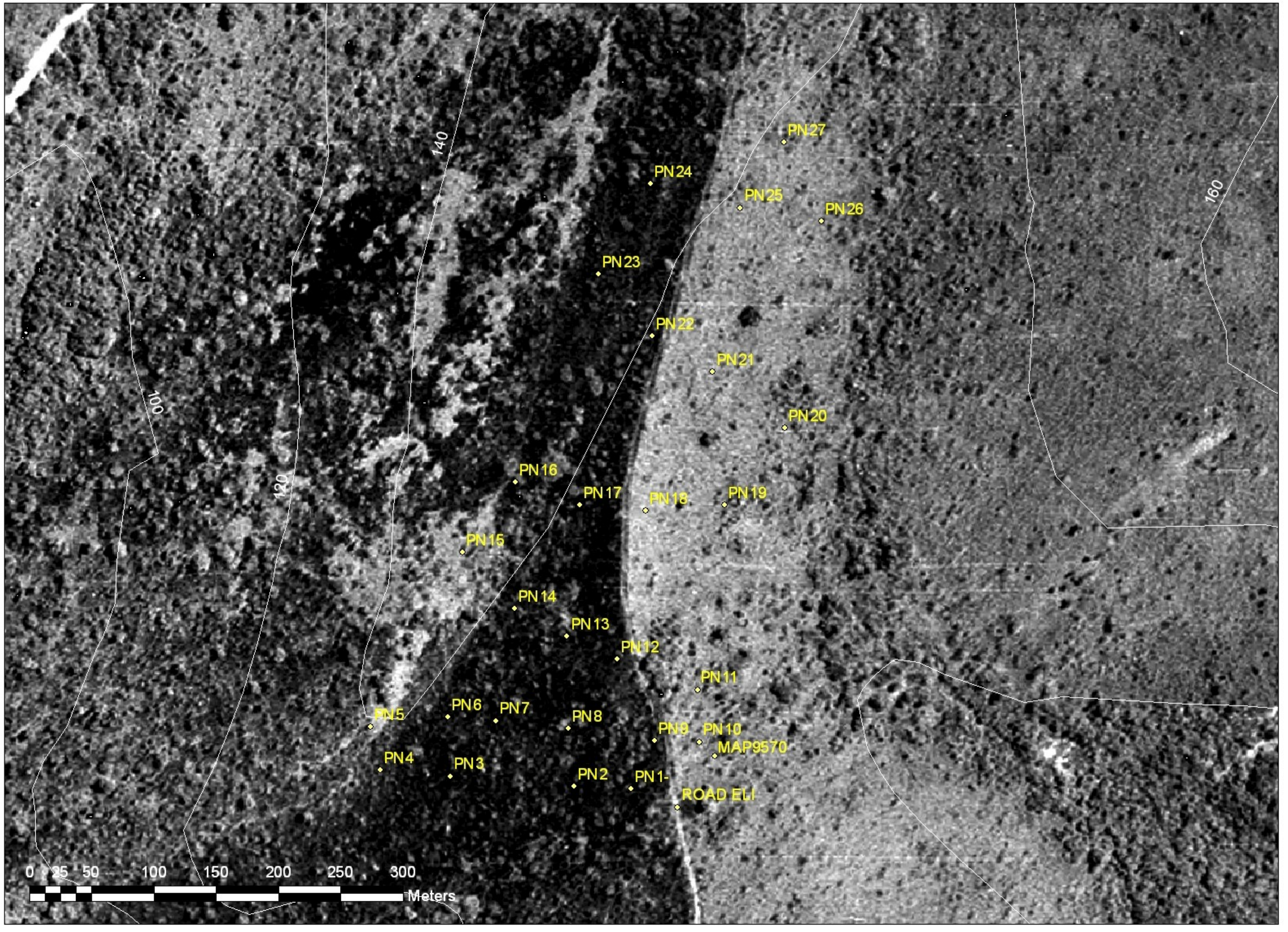
Apendix 1.1.1. Site 0894



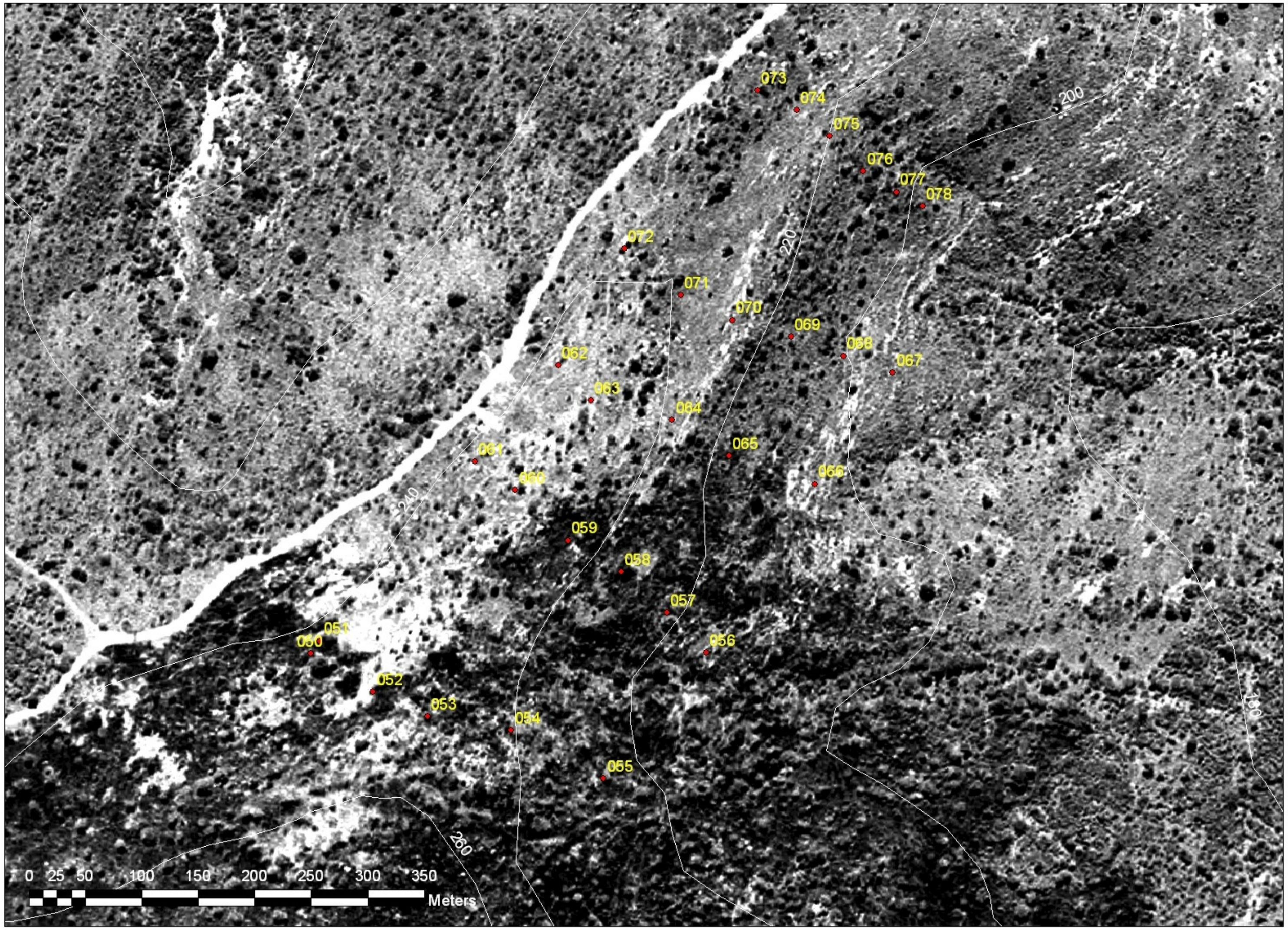
Appendix 1.1.2. Site 0898



Apendix 1.1.3. Site 9570

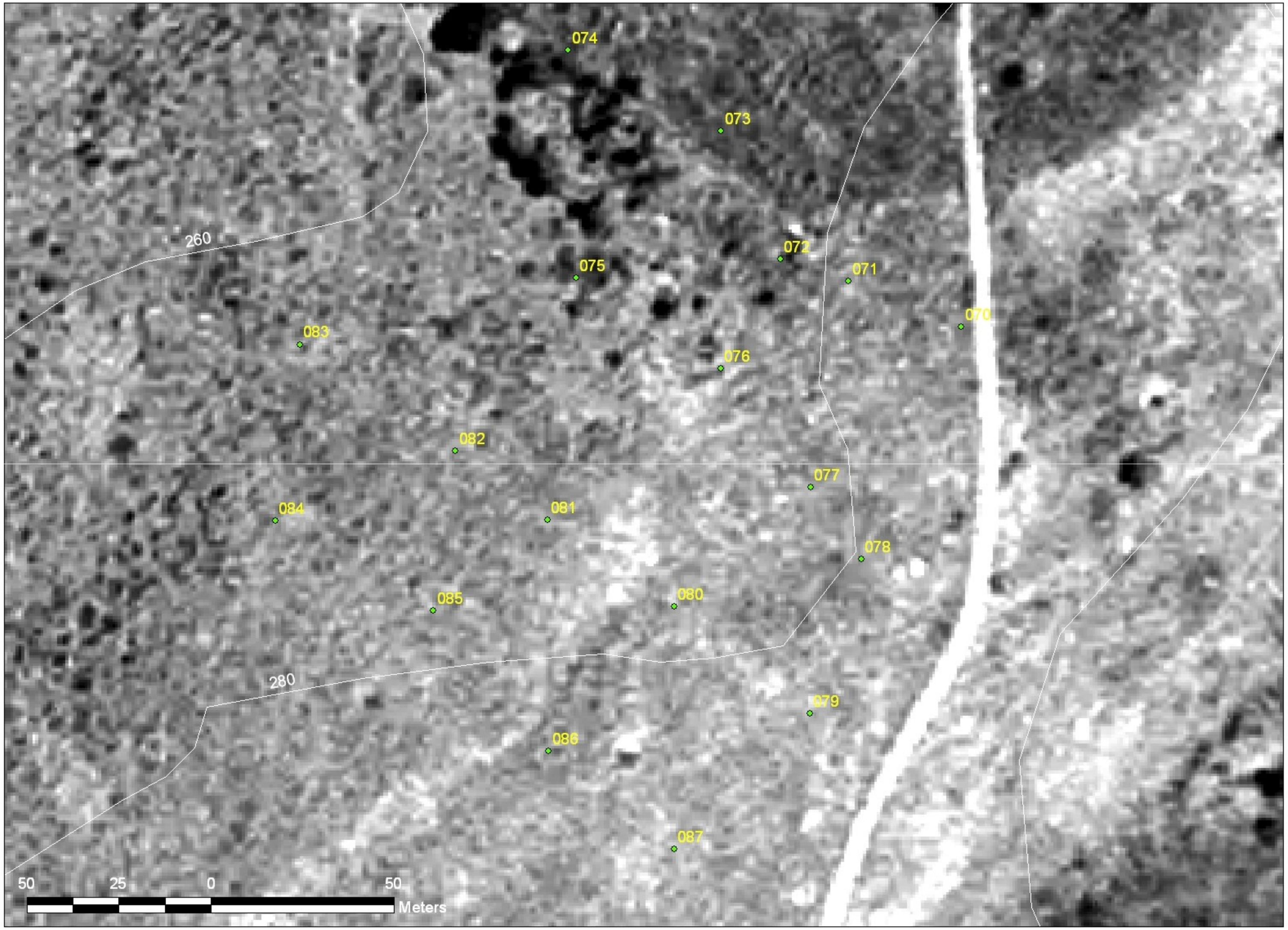


Apendix 1.1.4. Site 8168

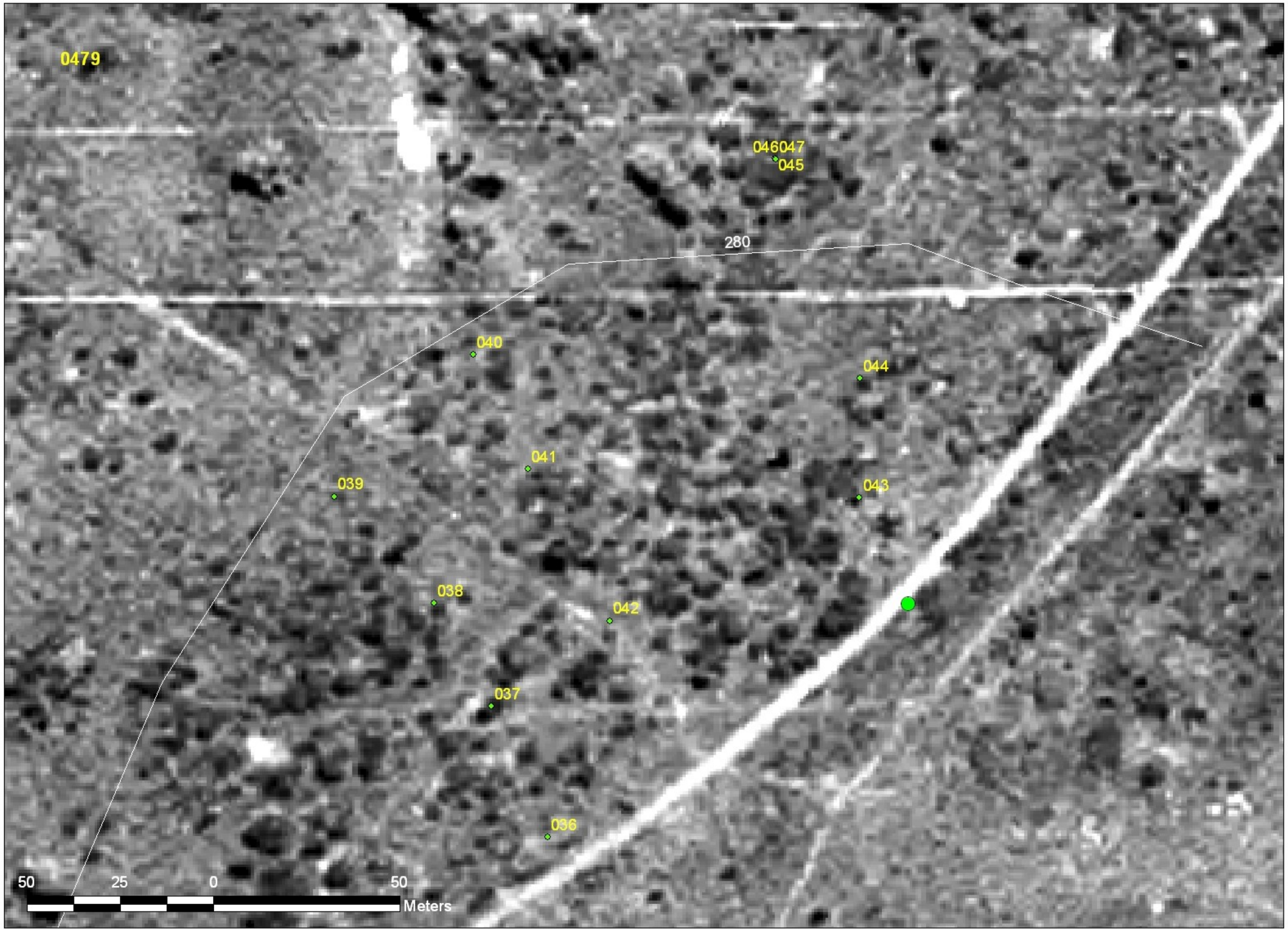


Appendix 1.2. Aerial photographs of the 'slight increase' sites showing the transects completed

Appendix 1.2.1. Site 9782

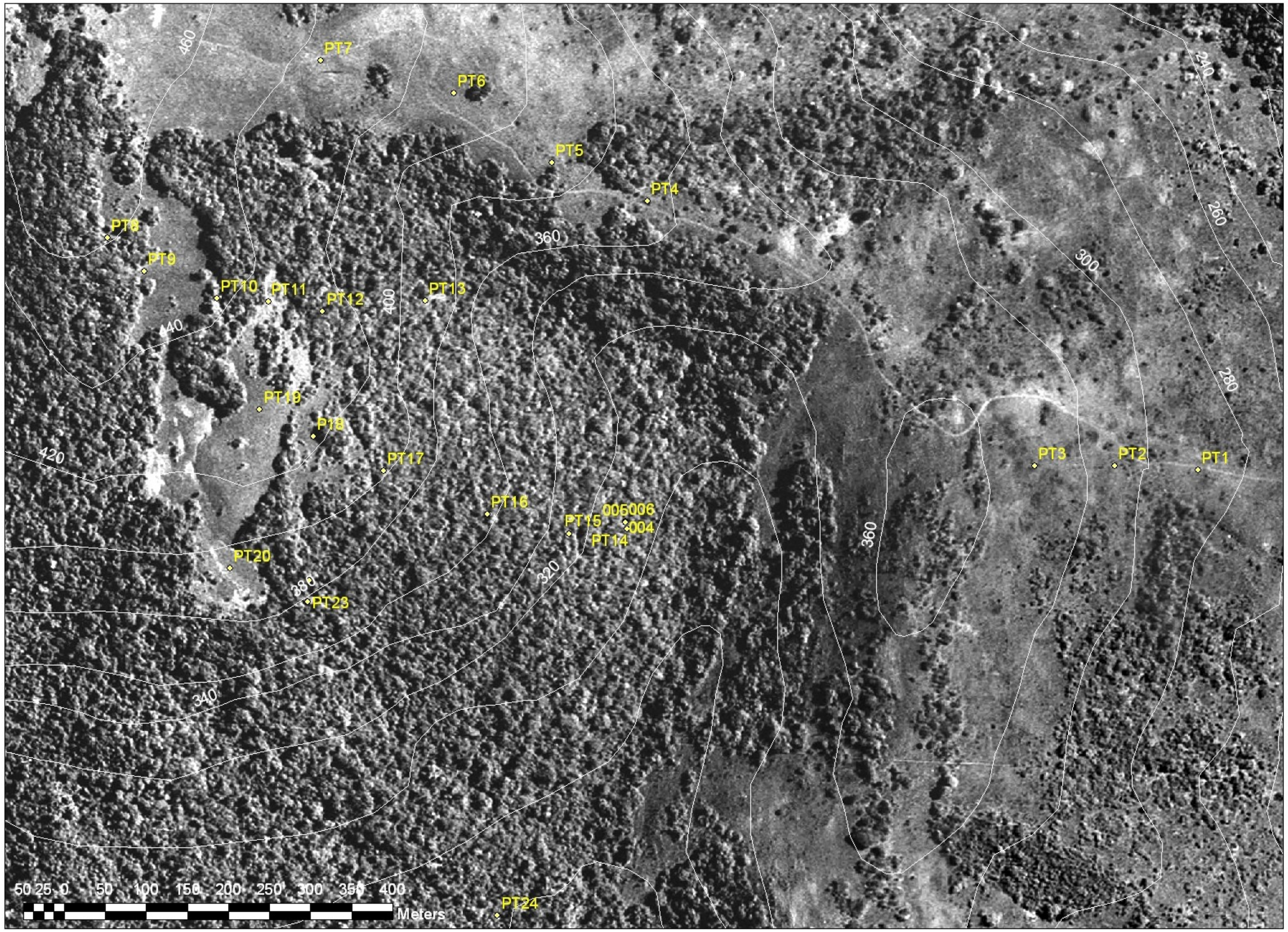


Appendix 1.2.2. Site 0479

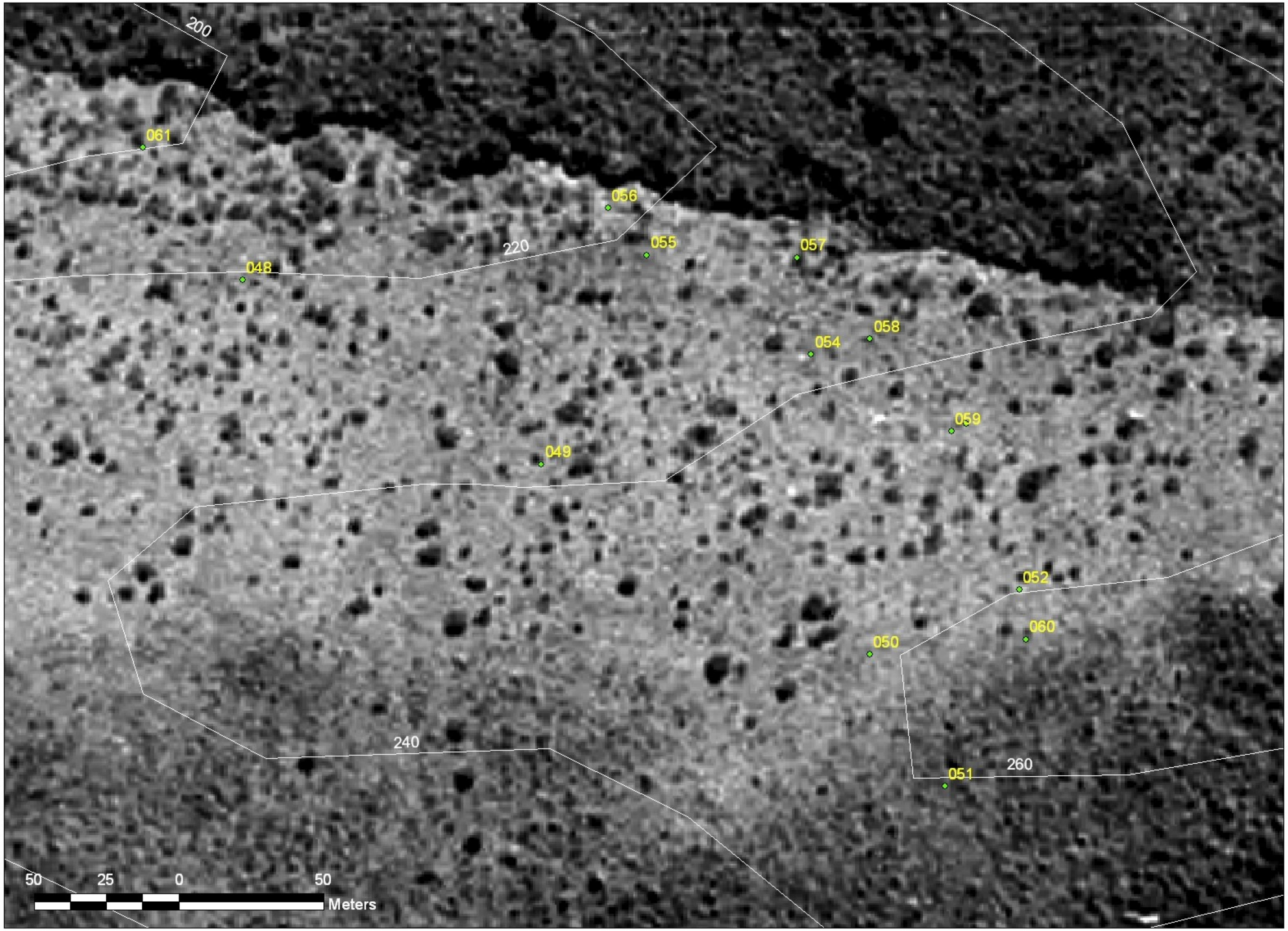


Appendix 1.3. Aerial photographs of the ‘increase’ sites showing the transects completed

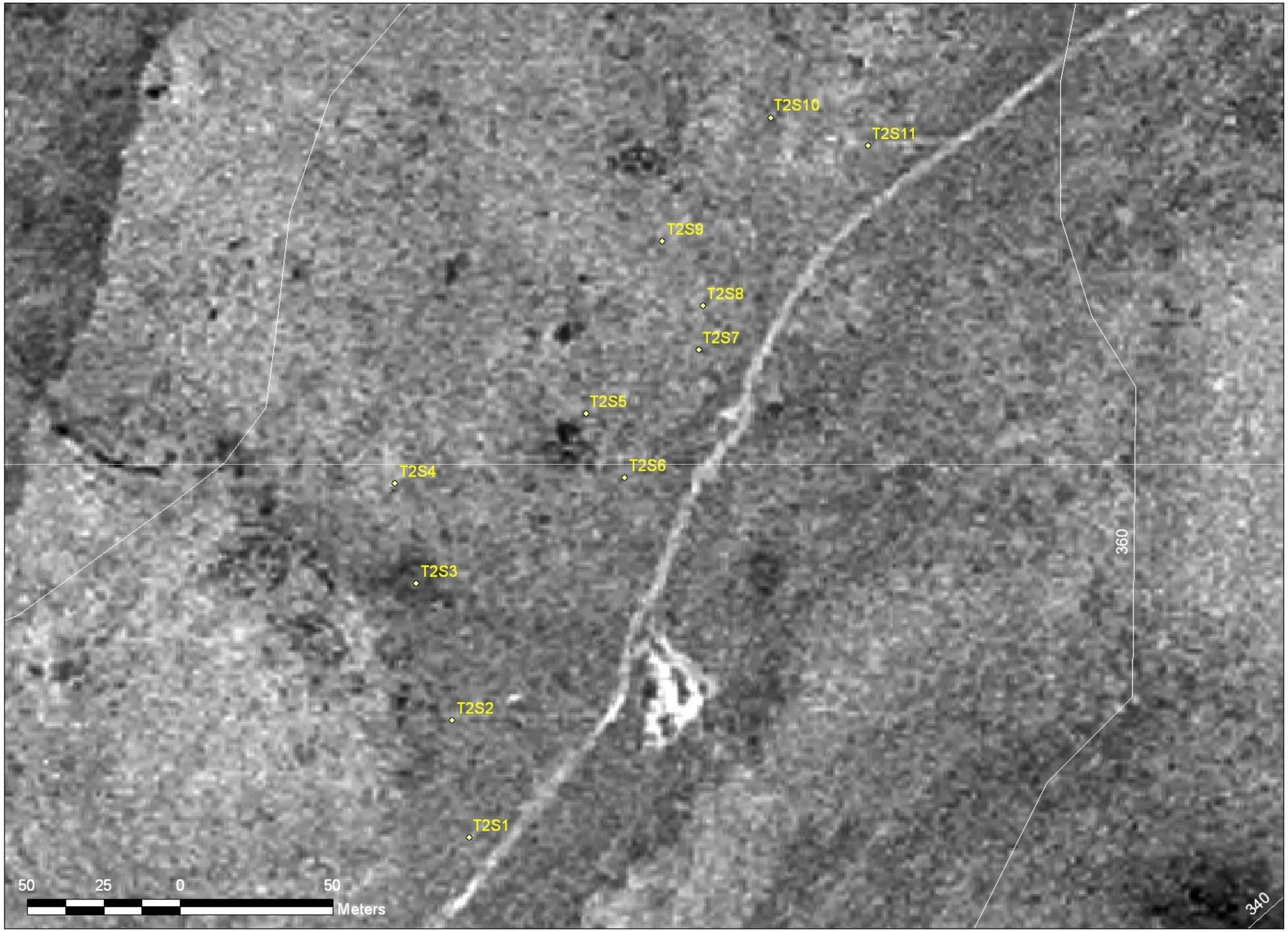
Appendix 1.3.1. Site 0994



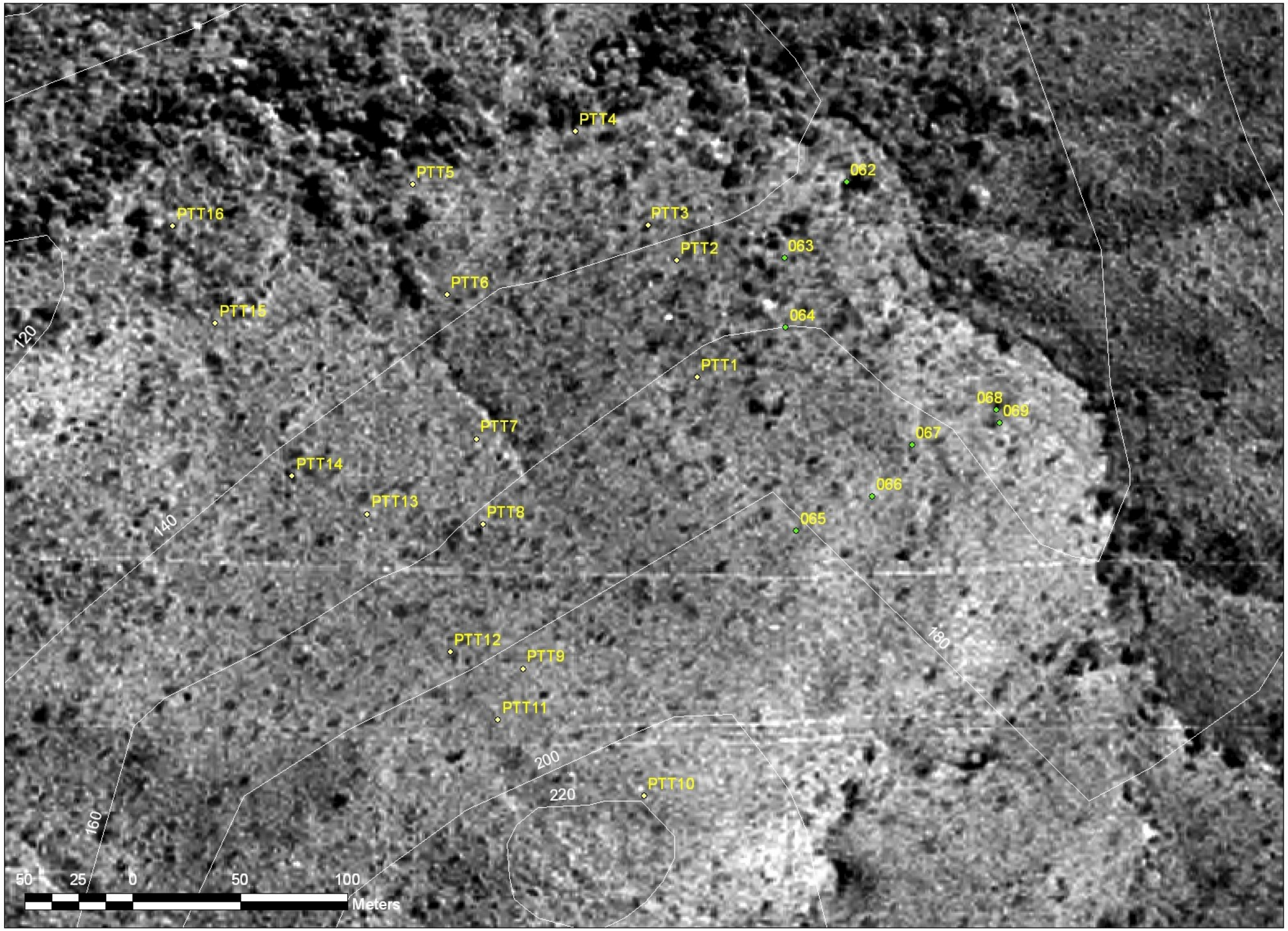
Appendix 1.3.2. Site 7561



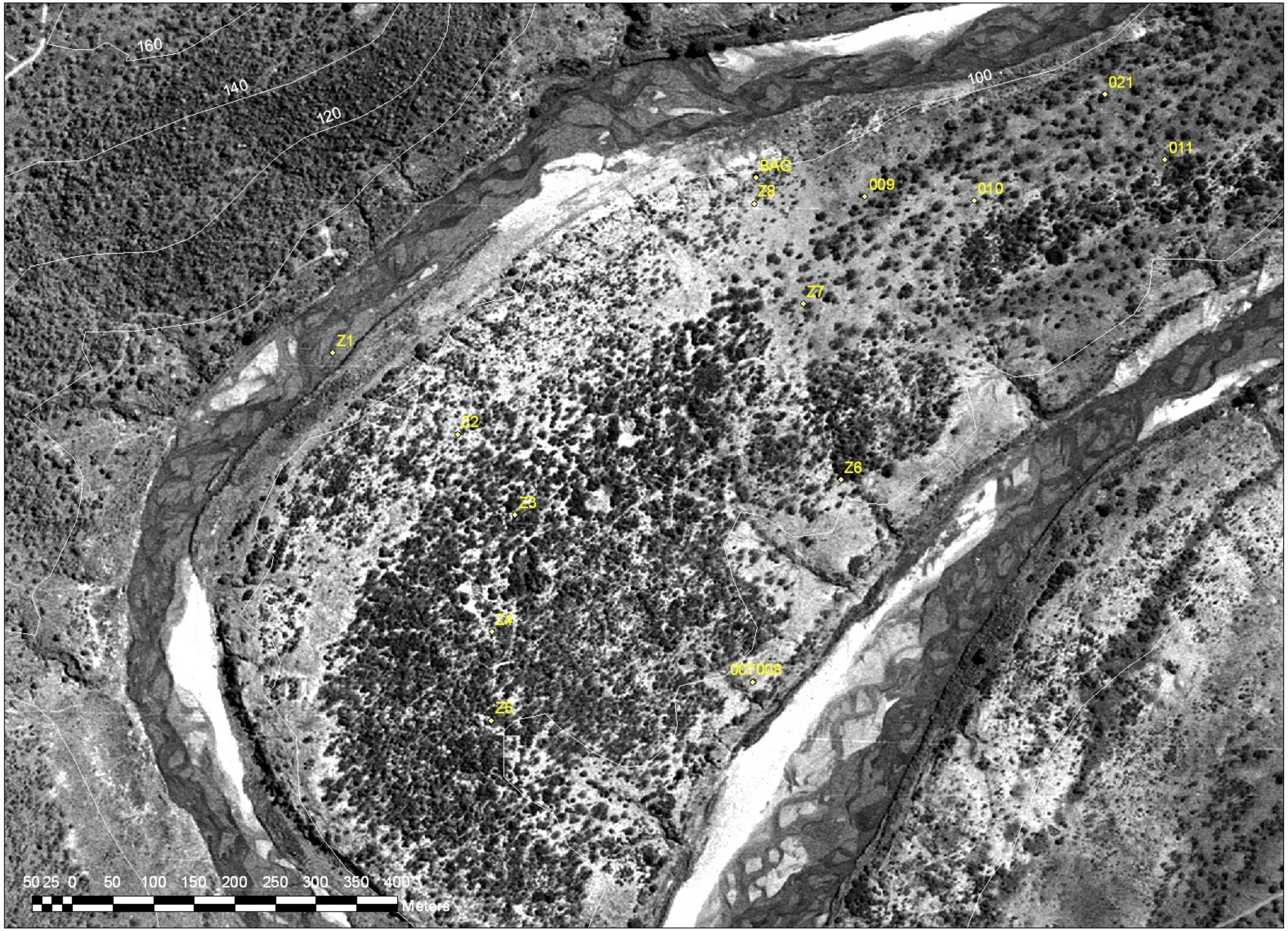
Appendix 1.3.3. Site 9579



Appendix 1.4.1. Site 9574

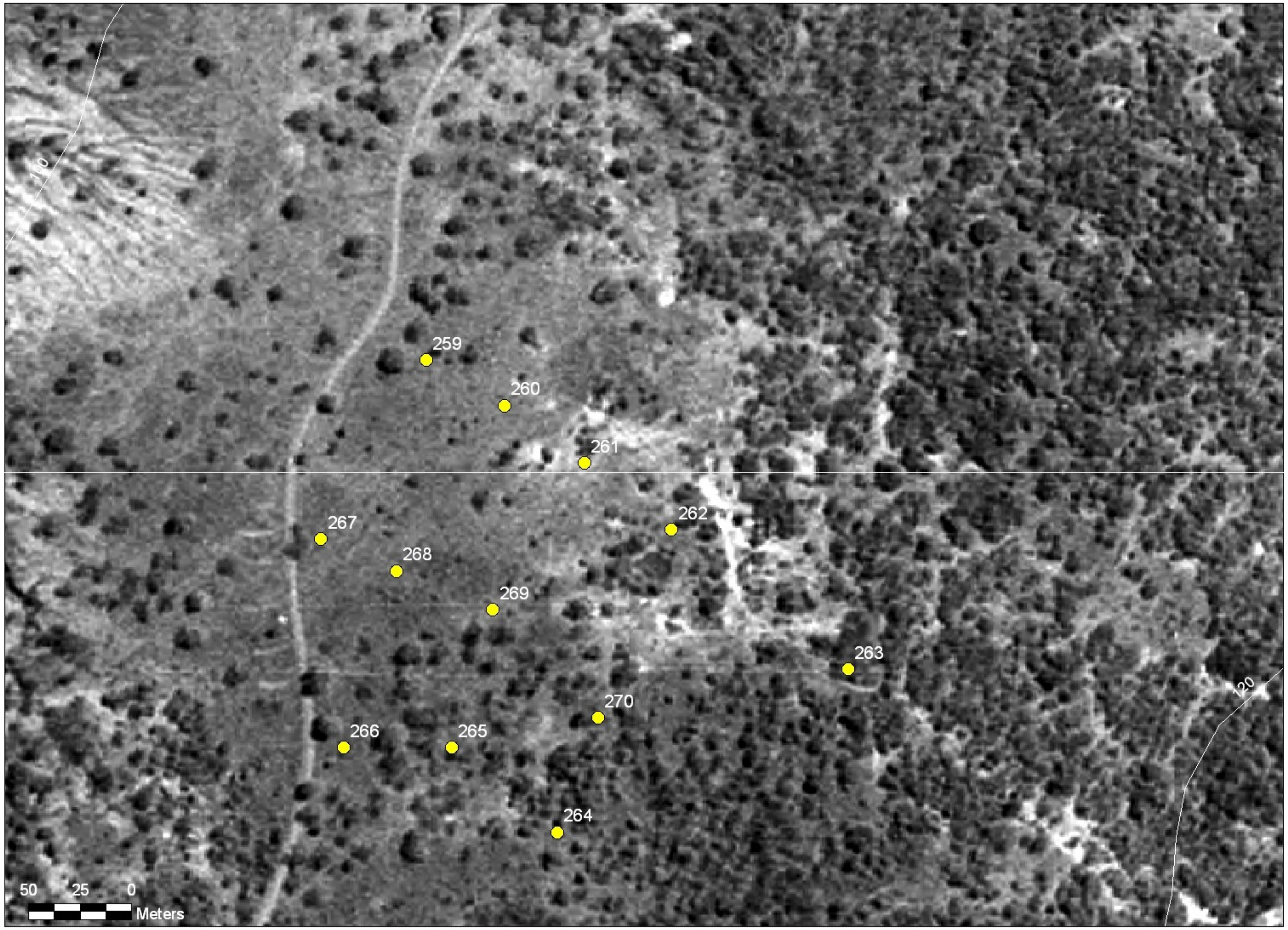


Appendix 1.4.2. Site 8278

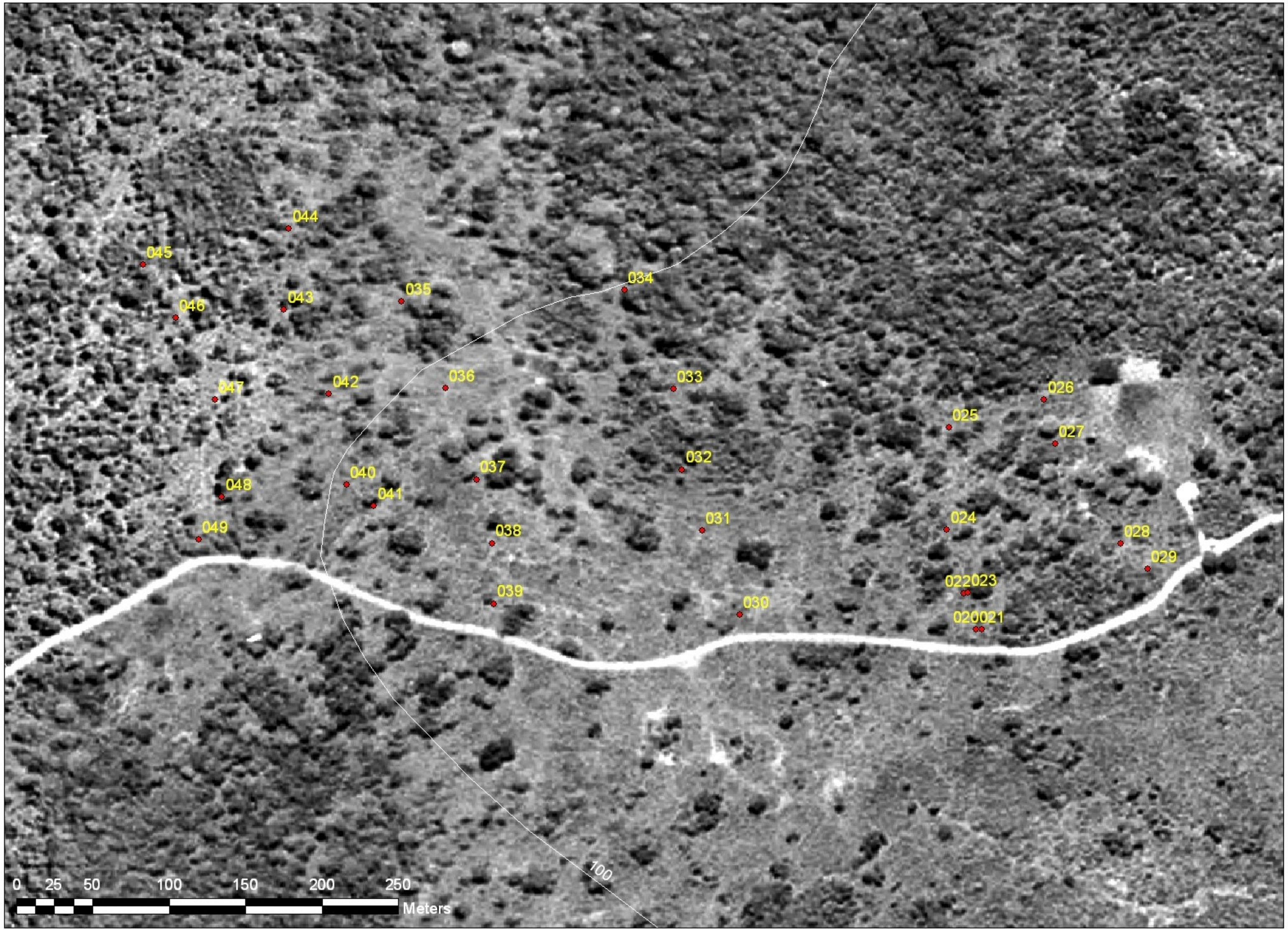


Appendix 1.5. Aerial photographs of the 'decrease' sites showing the transects completed

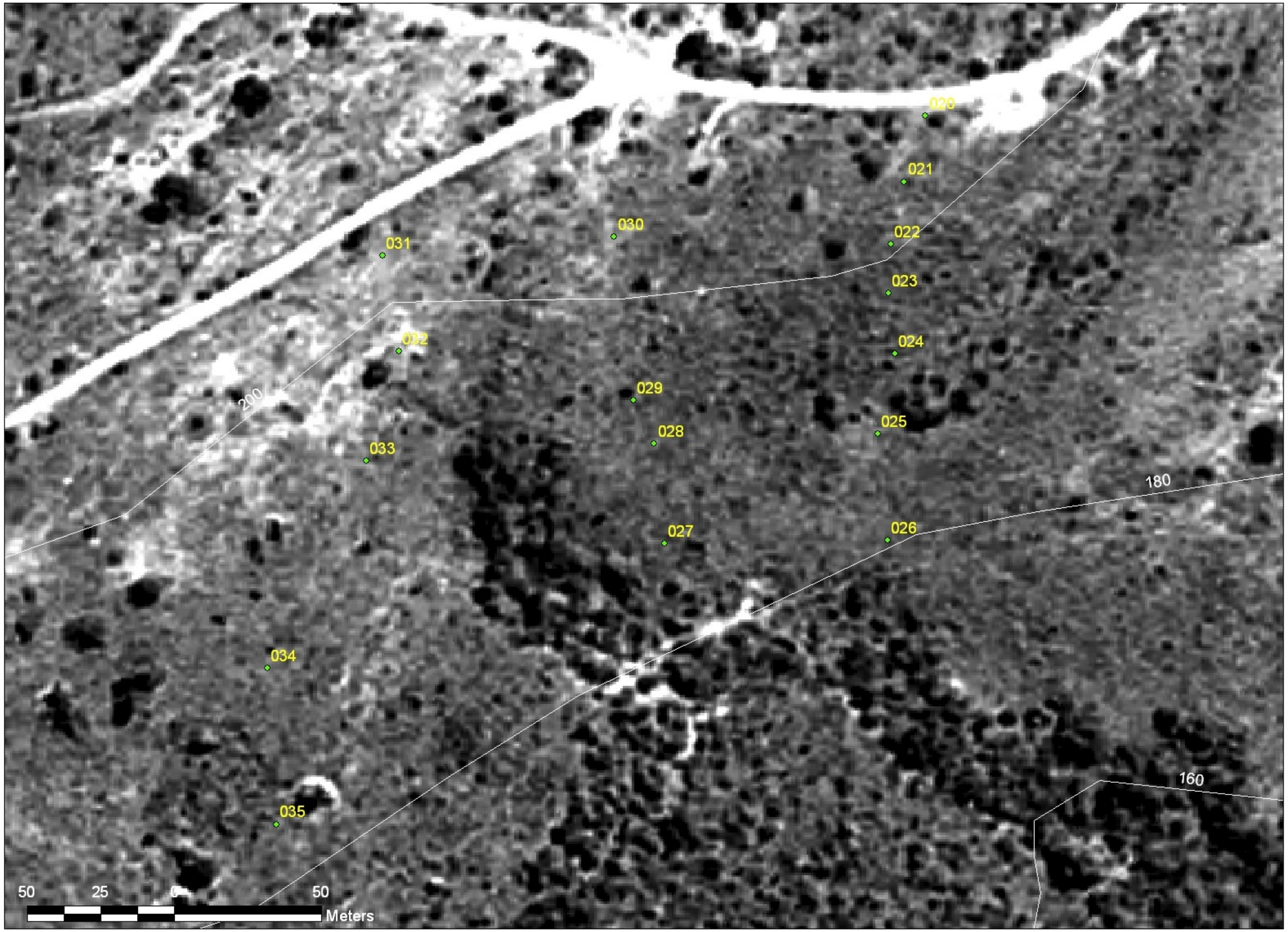
Appendix 1.5.1. Site 8376



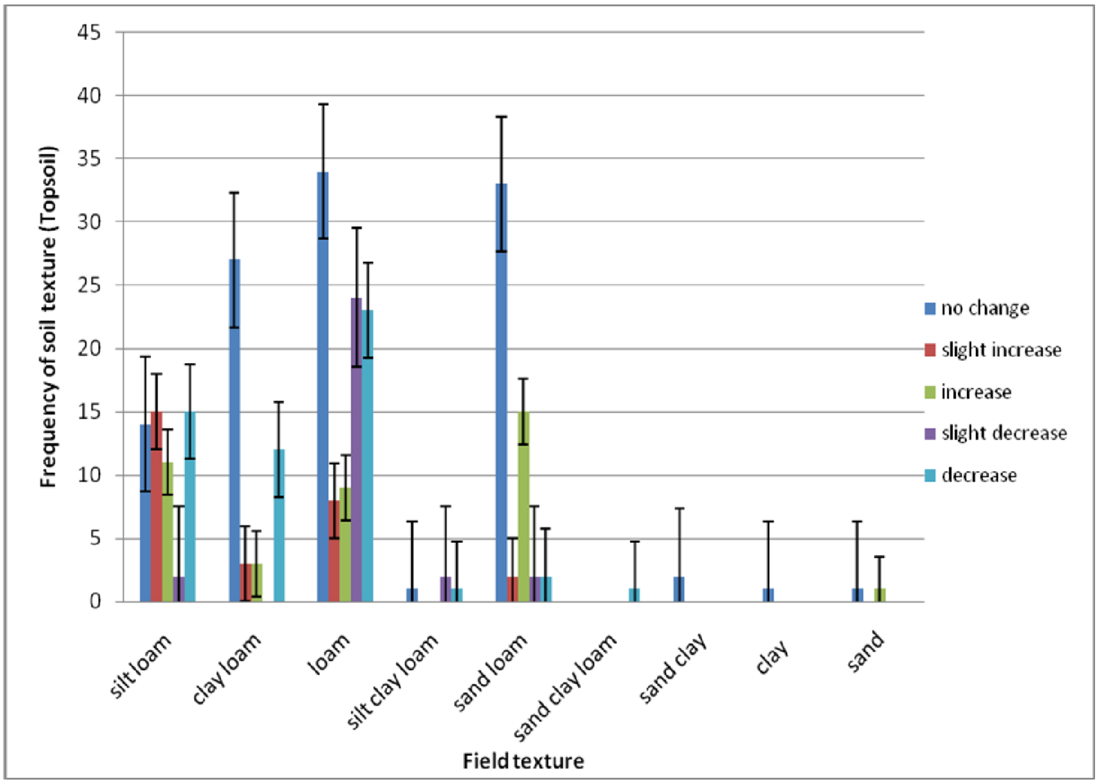
Appendix 1.5.2. Site 0991



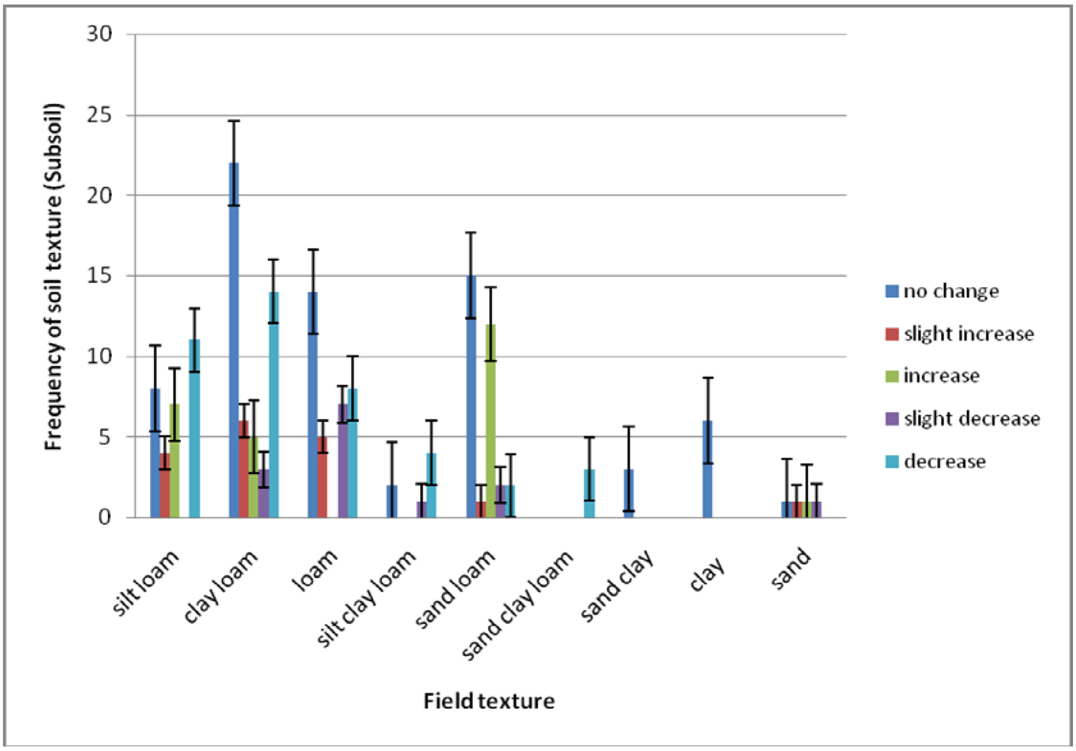
Appendix 1.5.3. Site 9985



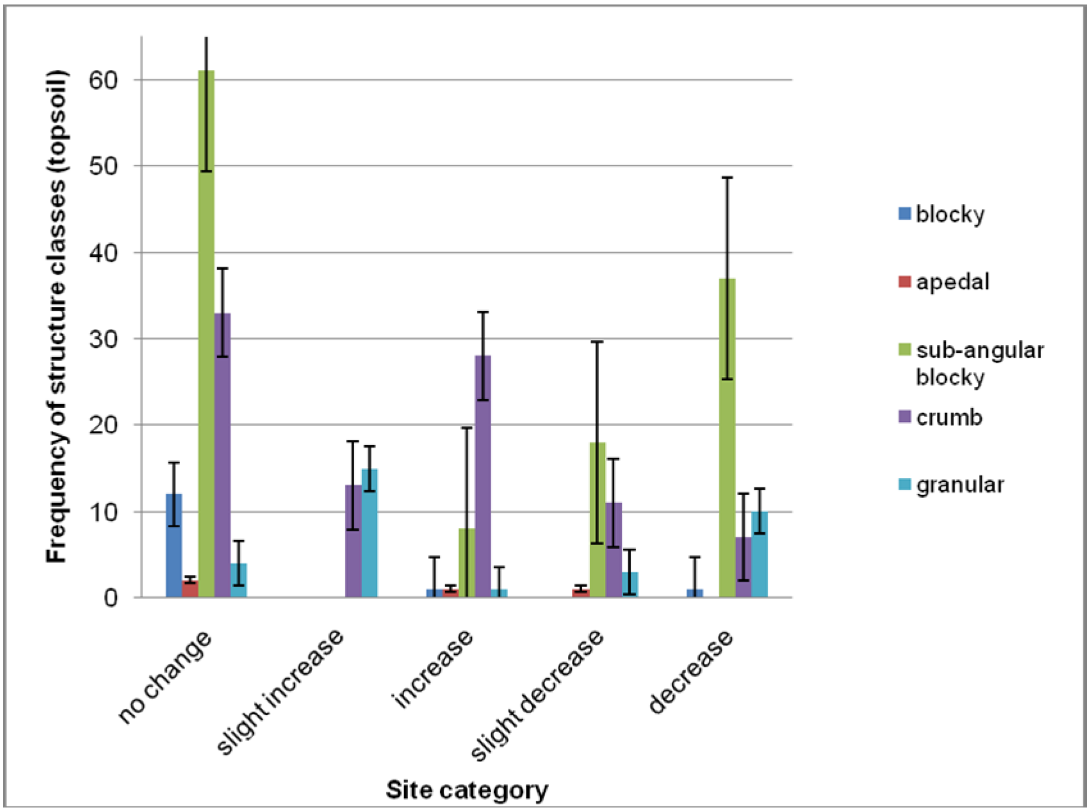
Appendix 2. Frequency bar graphs of the field data for the various sites



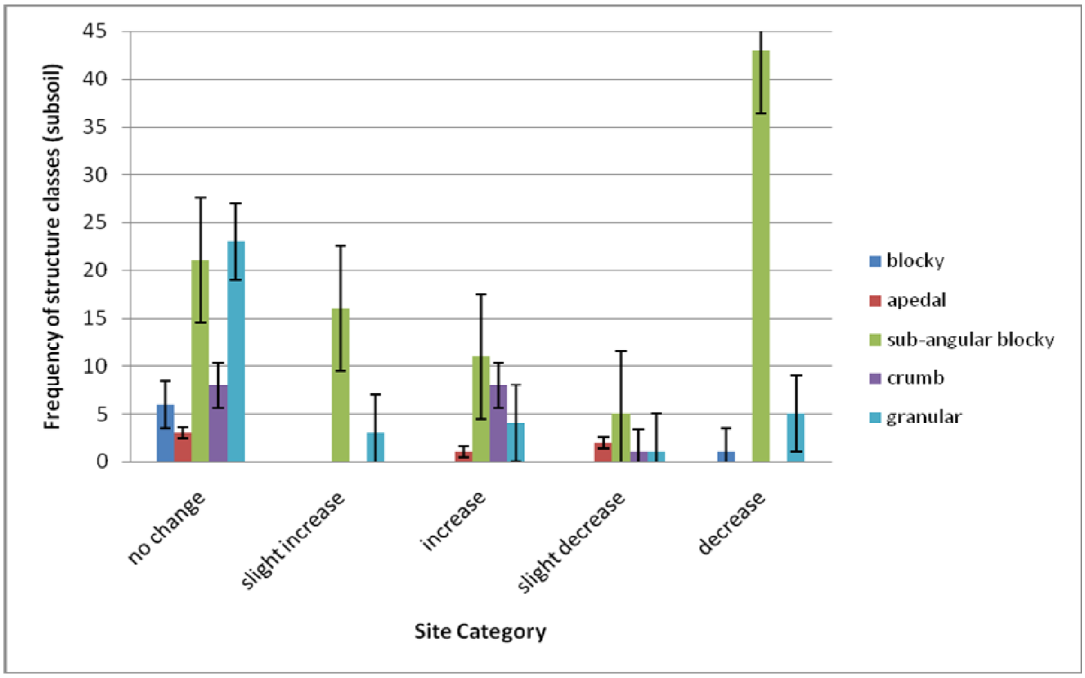
Appendix 2.1. Frequency of texture classes at each site category for the topsoil.



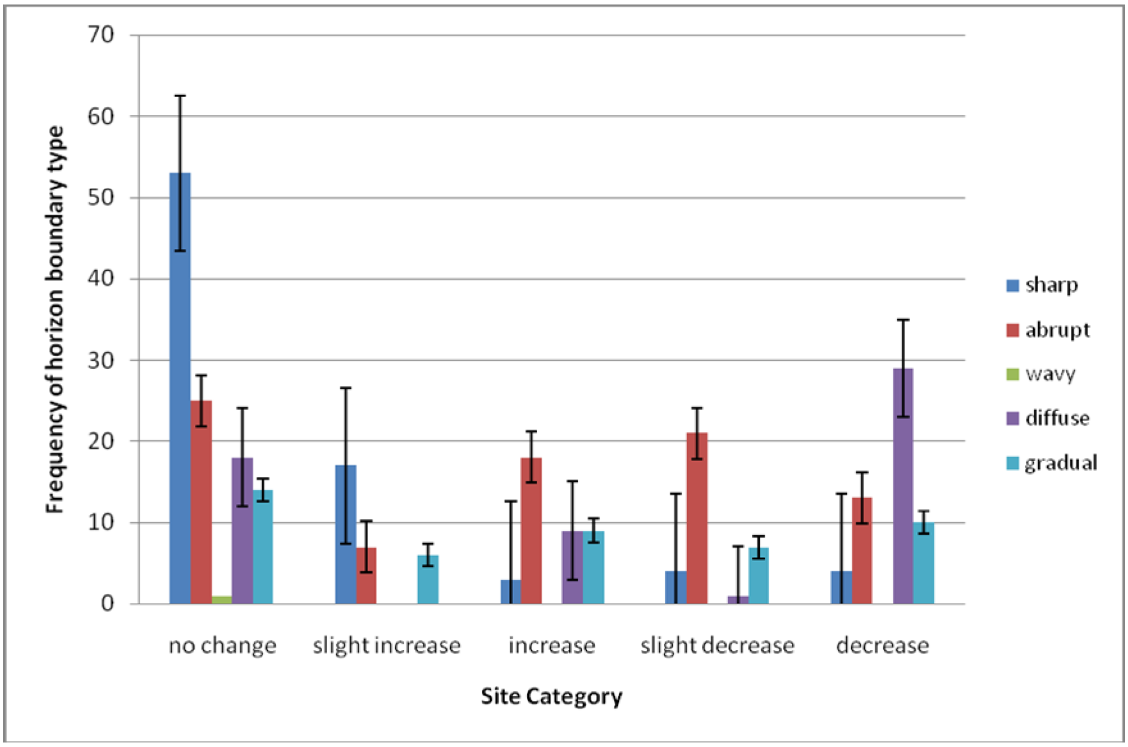
Appendix 2.2. Frequency of texture classes at each site category for the subsoil



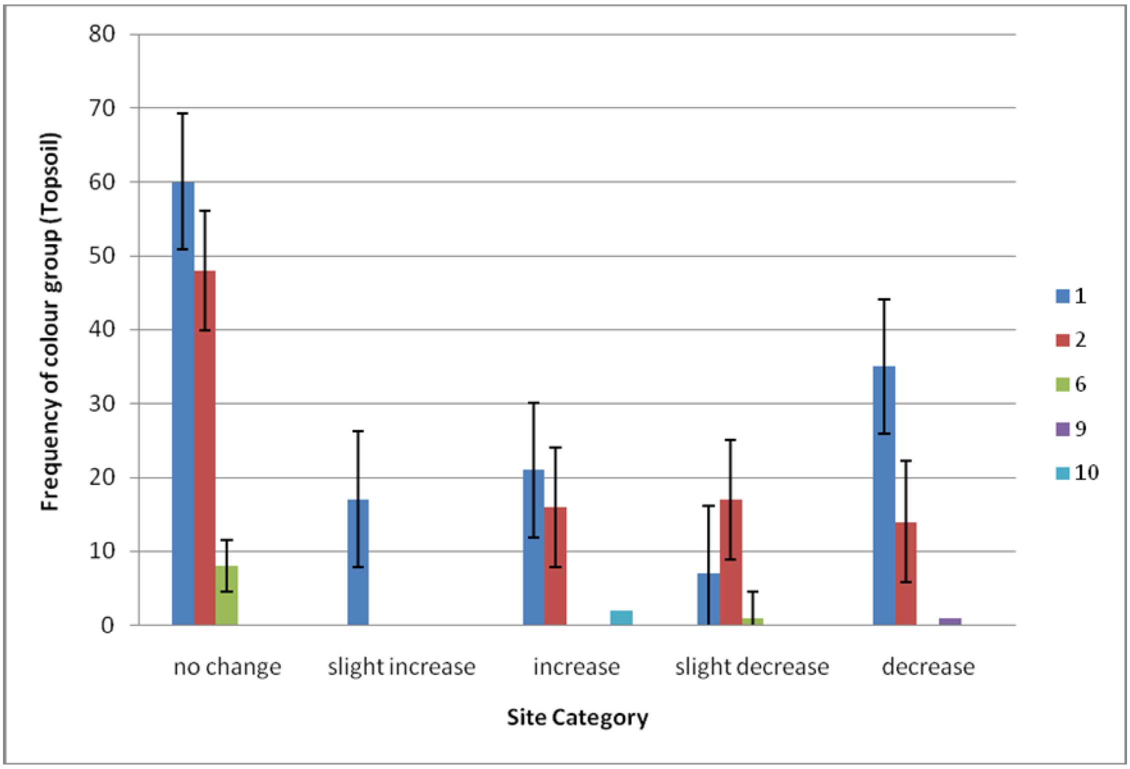
Appendix 2.3. Frequency of structure classes at each site category for the topsoil.



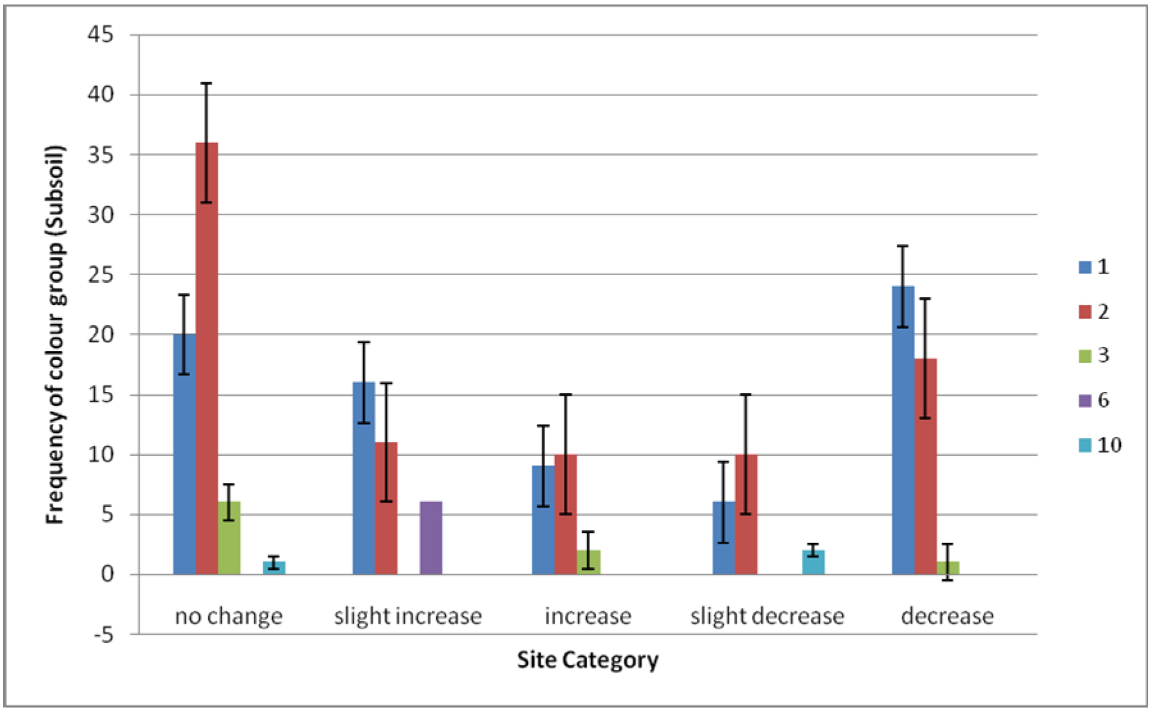
Appendix 2.4 Frequency of structure classes at each site category for the subsoil



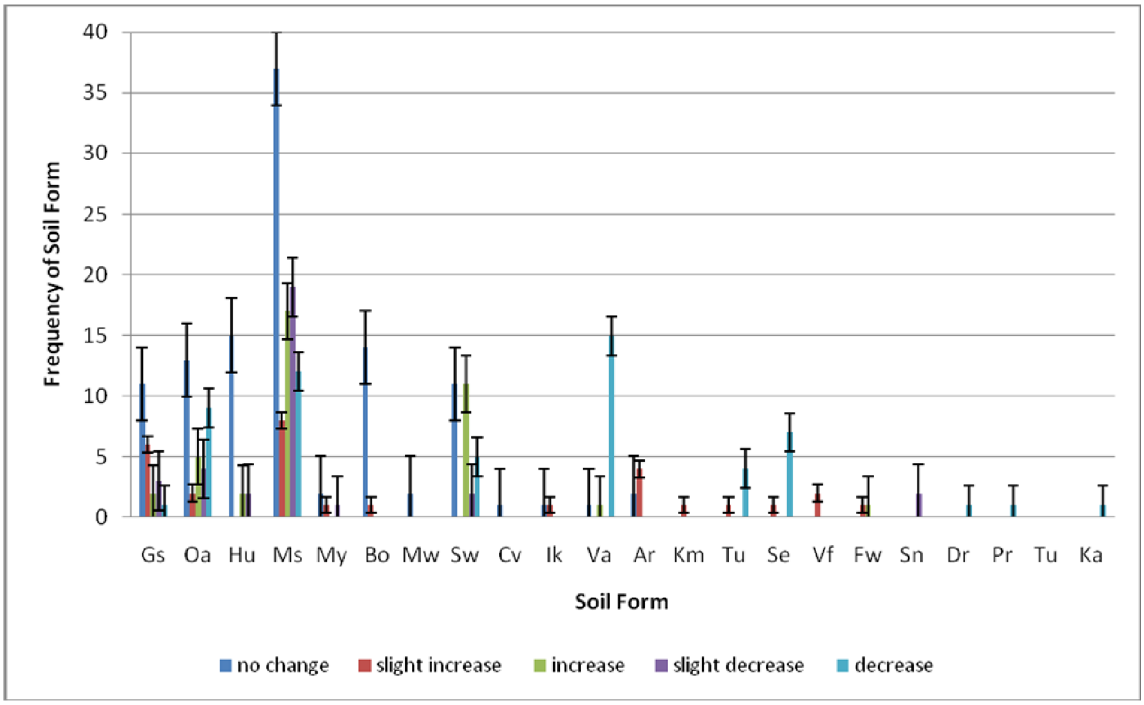
Appendix 2.5. Frequency of horizon boundary type for each site category.



Appendix 2.6. Frequency of colour groups at each site category for the topsoil



Appendix 2.7. Frequency of colour group at each site category for the subsoil.



Appendix 2.8. Frequency of soil form at each site category.

Appendix 3. Field data for the various sites

Appendix 3.1. Field data for the 'no-change' sites

				Topsoil				Subsoil				
Site number	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon Boundary	Structure (grade)	(size)	(class)
0894	4	Gs 1211	Orthic A	sharp	moderate	fine	blocky	Lithocutanic B	sharp	Weak	fine	apedal
0894	4	Gs 1211	Orthic A	abrupt	v. weak	v. fine	crumb	Lithocutanic B	sharp	weak	fine	apedal
0894	4	Oa 1210	Orthic A	wavy	moderate	fine	sub.ang blocky	Neocutanic B	diffuse	moderate	fine	sub.ang blocky
0894	4	Oa 1210	Orthic A	diffuse	moderate	medium	blocky	Neocutanic B	diffuse	moderate	fine	apedal
0894	4	Gs 1111	Orthic A	diffuse	moderate	medium	crumb	Lithocutanic B	diffuse	moderate	medium	sub.ang blocky
0894	4	Hu 2100	Orthic A	gradual	v.weak	v.fine	apedal	Red apedal B	diffuse	apedal	v. fine	apedal
0894	4	Ms 2100	Orthic A	sharp	moderate	medium	granular	hard rock				
0894	4	My 1100	Melanic A	distinct	moderate	fine	sub.ang blocky	Lithocutanic B	diffuse	moderate	fine	sub.ang blocky
0894	4	Bo 1110	Melanic A	diffuse	moderate	fine-med	granular	Pedocutanic B	diffuse	fine	fine	fine
0894	4	Mw 1000	Melanic A	sharp	moderate	fine-med	granular	hard rock				
0894	4	Ms 1100	Orthic A	sharp	v.weak	fine	crumb	hard rock				
0894	4	Ms 1100	Orthic A	sharp	v.weak	fine	crumb	hard rock				
0894	4	Ms 1100	Orthic A	sharp	v.weak	fine	crumb	hard rock				
0894	4	Ms 1100	Orthic A	sharp	weak	fine	crumb	hard rock				
0894	4	Ms 1100	Orthic A	sharp	weak	fine	crumb	hard rock				
0894	4	Hu 2100	Orthic A	sharp	weak	fine	crumb	Red apedal B	gradual	weak	fine	fine
0894	4	Ms 1100	Orthic A	sharp	weak	fine	crumb	hard rock				
0894	4	Oa 1110	Orthic A	sharp	weak	medium	sub.ang blocky	Neocutanic B	sharp	weak	medium	sub.ang blocky
0894	4	Ms 1100	Orthic A	sharp	weak	fine	crumb	hard rock				
0894	4	Ms 1100	Orthic A	sharp	weak	fine	crumb	hard rock				

Appendix 3.1. (continued)

Site number	% change	Soil Form + Family	Topsoil Horizon type	Topsoil Horizon boundary	Topsoil Structure (grade)	Topsoil Structure (size)	Topsoil Structure (class)	Subsoil Horizon type	Subsoil Horizon Boundary	Subsoil Structure (grade)	Subsoil Structure (size)	Subsoil Structure (class)
0894	4	Ms 1100	Orthic A	sharp	strong	medium	blocky	hard rock				
0894	4	Ms 1100	Orthic A	sharp	weak	fine	granular	hard rock				
0894	4	Ms 1100	Orthic A	sharp	weak	fine	granular	hard rock				
0894	4	Ms 1100	Orthic A	sharp	weak	fine	crumby	hard rock				
0894	4	Gs 1111	Orthic A	sharp	weak	fine	granular	Lithocutanic B	sharp	strong	medium	sub.ang blocky
0894	4	Gs 1111	Orthic A	distinct	strong	medium	crumb	Lithocutanic B	sharp	moderate	medium	sub.ang blocky
0894	4	My 2100	Melanic A	distinct	strong	medium	crumb	Lithocutanic B	sharp	moderate	medium	sub.ang blocky
0894	4	Ms 2100	Orthic A	abrupt	fine	fine	granular	hard rock				
0894	4	Gs 1211	Orthic A	diffuse	moderate	medium	crumb	Lithocutanic B	sharp	moderate	medium	sub.ang blocky
0894	4	Gs 1111	Orthic A	diffuse	moderate	medium	crumb	Lithocutanic B	sharp	moderate	medium	sub.ang blocky
0894	4	Ms 1100	Orthic A	abrupt	moderate	medium	crumb	hard rock				
0894	4	Oa 1210	Orthic A	distinct	moderate	medium	crumb	Neocutanic B	sharp	moderate	medium	sub.ang blocky
0894	4	Oa 1210	Orthic A	distinct	moderate	medium	crumb	Neocutanic B	sharp	moderate	medium	sub.ang blocky
0894	4	Oa 1210	Orthic A	gradual	moderate	fine	blocky	Neocutanic B	gradual	moderate	fine	sub.ang blocky
0894	4	Gs 1111	Orthic A	gradual	moderate	fine	sub.ang blocky	Lithocutanic B	gradual	moderate	fine	ang blocky
0894	4	Oa 1210	Orthic A	gradual	moderate	fine	sub.ang blocky	Neocutanic B	gradual	moderate	fine/mod	blocky
0894	4	Gs 1111	Orthic A	abrupt	moderate	fine	sub.ang blocky	Lithocutanic B	gradual	moderate	fine	sub.ang blocky
0894	4	Oa 1210	Orthic A	gradual	moderate	fine	sub.ang blocky	Neocutanic B	gradual	moderate	fine	sub.ang blocky
0894	4	Gs1111	Orthic A	diffuse	moderate	fine	sub.ang blocky	Lithocutanic B	sharp	moderate	fine	sub.ang blocky
0894	4	Gs1111	Orthic A	diffuse	moderate	fine	sub.ang blocky	Lithocutanic B	gradual	moderate	fine	sub.ang blocky
0898	2	Hu 2200	Orthic A	sharp	weak	fine	crumb	Red apedal B	gradual	apedal	fine	sub.ang blocky

Appendix 3.1. (continued)

			Topsoil					Subsoil				
Site number	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon Boundary	Structure (grade)	(size)	(class)
0898	2	Hu 1100	Orthic A	diffuse	moderate	medium	sub.ang blocky	Red apedal B	gradual	apedal	fine	apedal
0898	2	Hu 1100	Orthic A	diffuse	moderate	medium	sub.ang blocky	Red apedal B	gradual	apedal	fine	apedal
0898	2	Hu 1100	Orthic A	gradual	moderate	medium	sub.ang blocky	Red apedal B	gradual	apedal	fine	apedal
0898	2	Oa 1220	Orthic A	gradual	moderate	fine	sub.ang blocky	Neocutanic B	gradual	moderate	fine	sub.ang blocky
0898	2	Oa 1220	Orthic A	gradual	moderate	fine	sub.ang blocky	Neocutanic B	gradual	moderate	fine	sub.ang blocky
0898	2	Hu 2200	Orthic A	clear	moderate	medium	sub.ang blocky	Red apedal B	gradual	weak	fine	apedal
0898	2	Hu 2200	Orthic A	clear	moderate	fine	crumb	Red apedal B	gradual	weak	fine	apedal
0898	2	Sw 1111	Orthic A	clear	moderate	fine	crumb	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
0898	2	Hu 2200	Orthic A	clear	moderate	fine	crumb	Red apedal B	gradual	fine	fine	apedal
0898	2	Sw 1111	Orthic A	clear	fine	fine	crumb	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
0898	2	Cv 2100	Orthic A	clear	fine	fine	crumb	Yellow Brown apedal	gradual	apedal	fine	sub.ang blocky
0898	2	Hu 3100	Orthic A	distinct	moderate	medium	crumb	Red apedal B	gradual	apedal	fine	sub.ang blocky
0898	2	Hu 3100	Orthic A	distinct	moderate	medium	crumb	Red apedal B	gradual	apedal	fine	sub.ang blocky
0898	2	Hu 3100	Orthic A	distinct	moderate	medium	crumb	Red apedal B	gradual	apedal	fine	sub.ang blocky
0898	2	Oa 1210	Orthic A	distinct	moderate	medium	crumb	Neocutanic B	gradual	moderate	medium	sub.ang blocky
0898	2	Oa 1210	Orthic A	distinct	moderate	medium	crumb	Neocutanic B	gradual	moderate	medium	sub.ang blocky
0898	2	Hu 2200	Orthic A	gradual	moderate	fine	sub.ang blocky	Red apedal B	gradual	apedal	fiine-med	sub.ang blocky
0898	2	Hu 2200	Orthic A	gradual	moderate	fine	sub.ang blocky	Red apedal B	gradual	apedal	fine-med	sub.ang blocky
0898	2	Hu 2200	Orthic A	gradual	moderate	fine	sub.ang blocky	Red apedal B	gradual	apedal	fine	sub.ang blocky
0898	2	Sw 1111	Orthic A	gradual	moderate	fine	crumb	Pedocutanic B	gradual	moderate	medium	angular
0898	2	Oa 1210	Orthic A	gradual	moderate	fine	sub.ang blocky	Neocutanic B	gradual	fine	fine	apedal

Appendix 3.1. (continued)

			Topsoil					Subsoil				
Site number	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	Structure (size)	Structure (class)	Horizon type	Horizon Boundary	Structure (grade)	Structure (size)	Structure (class)
9570	4	Bo 1120	Melanic A	clear	fine	medium	blocky	Pedocutanic B	clear	moderate	medium	blocky
9570	4	Bo 1120	Melanic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	blocky
9570	4	My 1200	Melanic A	clear	moderate	medium	sub.ang blocky	Lithocutanic B	clear	moderate	medium	sub.ang blocky
9570	4	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
9570	4	Ms 1100	Orthic A	abrupt	weak	fine	apedal	hard rock				
9570	4	Bo 1110	Orthic A	clear	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	sub.ang blocky
9570	4	Ik 1100	Melanic A	clear	moderate	medium	sub.ang blocky	hard rock				
9570	4	Bo 1110	Melanic A	clear	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	sub.ang blocky
9570	4	Bo 1110	Melanic A	sharp	moderate	fine	sub.ang blocky	Pedocutanic B	sharp	strong	medium	sub.ang blocky
9570	4	Bo 1110	Melanic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	sub.ang blocky
9570	4	Bo 1110	Melanic A	clear	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	blocky
9570	4	Bo 1110	Melanic A	gradual	moderate	medium	blocky	Pedocutanic B	clear	moderate	medium	blocky
9570	4	Bo 1110	Melanic A	clear	moderate	medium	blocky	Pedocutanic B	clear	moderate	medium	sub.ang blocky
9570	4	Va 1211	Orthic A	sharp	moderate	fine	sub.ang blocky	Pedocutanic B	sharp	moderate	fine	sub.ang blocky
9570	4	Ms 1100	Orthic A	abrupt	moderate	fine	sub.ang blocky	hard rock				
9570	4	Bo 1110	Melanic A	clear	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	blocky
9570	4	Bo 1110	Melanic A	clear	moderate	medium	blocky	Pedocutanic B	clear	moderate	medium	blocky
9570	4	Ar 1100	Vertic A	abrupt	weak	fine	blocky	hard rock				
9570	4	Rg 2000	Vertic A	clear	moderate	medium	blocky	G	clear	moderate	medium	blocky
9570	4	Rg 2000	Vertic A	clear	moderate	medium	blocky	G	clear	moderate	medium	blocky
9570	4	Ar 1100	Vertic A	abrupt	moderate	medium	blocky	hard rock				
9570	4	Bo 1100	Melanic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	sub.ang blocky

Appendix 3.1. (continued)

			Topsoil					Subsoil				
Site number	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon Boundary	Structure (grade)	(size)	(class)
9570	4	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
9570	4	Ms 1100	Orthic A	abrupt	fine	fine	sub.ang blocky	hard rock				
9570	4	Bo 1100	Melanic A	clear	moderate	medium	sub.ang blocky	Pedocutanic B	clear	moderate	medium	sub.ang blocky
9570	4	Rg 2000	Vertic A	clear	moderate	medium	sub.ang blocky	G	clear	moderate	medium	blocky
9570	4	Bo 1110	Melanic A	clear	moderate	fine	granular	Pedocutanic B	clear	moderate	fine	sub.ang blocky
8168	3	Ms 1100	Orthic A	sharp	fine	fine	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	sharp	fine	fine	sub.ang blocky	hard rock				
8168	3	Sw 1111	Orthic A	diffuse	fine	fine	sub.ang blocky	Pedocutanic B	sharp	strong	coarse	ang.blocky
8168	3	Sw 1111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	sharp	moderate	medium	sub.ang blocky
8168	3	Ms 1100	Orthic A	abrupt	fine	medium	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Mw 1100	Melanic A	abrupt	strong	coarse	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	fine	fine	crumb	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Ms 2100	Orthic A	abrupt	fine	fine	crumb	hard rock				
8168	3	Sw 1111	Orthic A	diffuse	fine	fine	sub.ang blocky	Pedocutanic B	sharp	moderate	medium	sub.ang blocky
8168	3	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Ms 2100	Orthic A	abrupt	fine	fine	crumb	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	fine	fine	sub.ang blocky	hard rock				
8168	3	Sw 1111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	sharp	moderate	medium	sub.ang blocky
8168	3	Ms 2100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	fine	medium	sub.ang blocky	hard rock				

Appendix 3.1. (continued)

			Topsoil					Subsoil				
Site number	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon Boundary	Structure (grade)	(size)	(class)
8168	3	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8168	3	Sw 1111	Orthic A	diffuse	fine	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
8168	3	Sw 2111	Orthic A	diffuse	fine	medium	sub.ang blocky	Pedocutanic B	sharp	moderate	coarse	sub.ang blocky
8168	3	Sw 2111	Orthic A	diffuse	fine	fine	sub.ang blocky	Pedocutanic B	sharp	moderate	medium	sub.ang blocky
8168	3	Sw 2111	Orthic A	diffuse	strong	medium	sub.ang blocky	Pedocutanic B	sharp	moderate	medium	sub.ang blocky
8168	3	Sw 2111	Orthic A	diffuse	strong	medium	sub.ang blocky	Pedocutanic B	distinct	strong	medium	sub.ang blocky
8168	3	Ms 1100	Orthic A	abrupt	strong	medium	sub.ang blocky	hard rock				
8168	3	Sw 2111	Orthic A	diffuse	fine	medium	sub.ang blocky	Pedocutanic B	sharp	strong	medium	sub.ang blocky
8168	3	Ms 1100	Orthic A	abrupt	strong	medium	sub.ang blocky	hard rock				
8168	3	Ms 1100	Orthic A	abrupt	fine	fine	sub.ang blocky	hard rock				

Appendix 3.2. Field data collected for the 'slight increase' sites.

				Topsoil				Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	Structure (size)	Structure (class)	Horizon type	Horizon boundary	Structure (grade)	Structure (size)	Structure (class)
9782	10	Km 1110	Orthic A	sharp	weak	fine	granular	E	sharp	weak	fine	granular
9782	10	Tu 1110	Orthic A	gradual	weak	fine	granular	Neocutanic B	diffuse	moderate	fine	sub.ang blocky
9782	10	Ms 1100	Orthic A	sharp	weak	fine	granular	no sub horizon				
9782	10	Ar 1100	Vertic A	abrupt	moderate	fine	crumb	no sub horizon				
9782	10	Ik 2100	Melanic A	sharp	moderate	fine	crumb	no sub horizon				
9782	10	Ar 1100	Vertic A	sharp	moderate	fine	crumb	no sub horizon				
9782	10	Bo 1110	Melanic A	gradual	moderate	medium	crumb	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
9782	10	Ms 1100	Orthic A	sharp	weak	fine	granular	no sub horizon				
9782	10	Ms 2100	Orthic A	sharp	weak	fine	granular	no sub horizon				
9782	10	Gs 2121	Orthic A	gradual	weak	fine	granular	Lithocutanic B	diffuse	moderate	medium	sub.ang blocky
9782	10	Gs 2121	Orthic A	gradual	weak	fine	granular	Lithocutanic B	diffuse	moderate	medium	sub.ang blocky
9782	10	Ms 2100	Orthic A	abrupt	weak	fine	granular	no sub horizon				
9782	10	Ms 1100	Orthic A	abrupt	moderate	medium	crumb	no sub horizon				
9782	10	Ar 1100	Vertic A	abrupt	moderate	fine	crumb	no sub horizon				
9782	10	Ms 1100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
9782	10	My 1100	Melanic A	gradual	moderate	fine	crumb	Lithocutanic B	diffuse	moderate	medium	sub.ang blocky
9782	10	Ar 1100	Vertic A	abrupt	moderate	medium	crumb	no sub horizon				
9782	10	Ms 2100	Orthic A	abrupt	weak	fine	granular	no sub horizon				
9782	10	Ms 2100	Orthic A	sharp	weak	fine	granular	no sub horizon				
0479	13	Gs 1111	Orthic A	sharp	weak	fine	granular	Lithocutanic B	distinct	weak	fine	sub.ang blocky
0479	13	Oa 1000	Orthic A	sharp	weak	fine	granular	Neocutanic B	distinct	strong	medium	sub.ang blocky
0479	**13**	Se 2210	Orthic A	sharp	moderate	fine	crumb	Pedocutanic B	sharp	moderate	medium	sub.ang blocky

Appendix 3.2. (continued)

			Topsoil					Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)
0479	13	Oa 1000	Orthic A	sharp	weak	fine	granular	Neocutanic B	distinct	weak	medium	sub.ang blocky
0479	13	Vf 1110	Orthic A	distinct	weak	fine	granular	E	distinct	weak	fine	sub.ang blocky
0479	13	Fw	Orthic A	distinct	weak	fine	granular	E1	distinct	weak	fine	sub.ang blocky
0479	13	Gs 1111	Orthic A	distinct	weak	fine	crumb	Lithocutanic B	distinct	weak	fine	sub.ang blocky
0479	13	Gs 1111	Orthic A	distinct	weak	fine	crumb	Lithocutanic B	distinct	weak	fine	sub.ang blocky
0479	13	Gs 1111	Orthic A	distinct	weak	fine	crumb	Lithocutanic B	distinct	moderate	moderate	sub.ang blocky
0479	13	Vf 1110	Orthic A	distinct	weak	fine	crumb	E	distinct	weak	fine	granular

Appendix 3.3. Field data collected for the 'increase' sites.

				Topsoil				Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)
0994	35	Sw 1111	Orthic A	gradual	fine	fine	crumb	Pedocutanic B	gradual	fine	fine	sub.ang blocky
0994	35	Hu 2100	Orthic A	gradual	fine	fine	crumb	Red apedal B	gradual	fine	fine	apedal
0994	35	Sw 1111	Orthic A	gradual	fine	fine	granular	Pedocutanic B	gradual	fine	fine	sub.ang blocky
0994	35	Ms 1100	Orthic A	abrupt	fine	fine	sub.ang blocky	no sub horizon				
0994	35	Sw 1111	Orthic A	gradual	fine	fine	crumb	Pedocutanic B	gradual	fine	fine	sub.ang blocky
0994	35	Ms 1100	Orthic A	abrupt	fine	fine	crumb	no sub horizon				
0994	35	Gs 1211	Orthic A	gradual	fine	fine	crumb	Lithocutanic B	gradual	fine	fine	sub.ang blocky
0994	35	Ms 1100	Orthic A	abrupt	fine	fine	crumb	no sub horizon				
0994	35	Sw 1111	Orthic A	gradual	fine	fine	crumb	Pedocutanic B	gradual	fine	fine	sub.ang blocky
0994	35	Oa 1110	Orthic A	gradual	fine	fine	crumb	Neocutanic B	gradual	fine	fine	sub.ang blocky
0994	35	Ms 1100	Orthic A	abrupt	fine	fine	crumb	no sub horizon				
0994	35	Va 2111	Orthic A	gradual	fine	fine	crumb	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
0994	35	Hu 2100	Orthic A	distinct	fine	fine	crumb	Red apedal B	gradual	fine	fine	apedal
9579	47	Sw 1121	Orthic A	gradual	weak	fine	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
9579	47	Sw 1121	Orthic A	diffuse	weak	fine	blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
9579	47	Sw 1121	Orthic A	diffuse	weak	fine	sub.ang blocky	Pedocutanic B	diffuse	weak	fine	sub.ang blocky
9579	47	Sw 1121	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	course	sub.ang blocky
9579	47	Sw 1111	Orthic A	diffuse	apedal	fine	crumb	Pedocutanic B	diffuse	moderate	loose	sub.ang blocky
9579	47	Sw 1111	Orthic A	diffuse	apedal	fine	crumb	Pedocutanic B	diffuse	moderate	loose	sub.ang blocky
9579	47	Sw 1211	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	coarse	medium	sub.ang blocky
9579	47	Oa 1110	Orthic A	diffuse	moderate	medium	sub.ang blocky	Neocutanic B	diffuse	weak	fine	sub.ang blocky
9579	47	Oa 1110	Orthic A	diffuse	weak	fine	sub.ang blocky	Neocutanic B	diffuse	weak	fine	sub.ang blocky

Appendix 3.3. (continued)

			Topsoil					Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)
9579	47	Fw 1110	Orthic A	clear	fine	fine	crumb	E	clear	weak	fine	sub.ang blocky
9579	47	Oa 1110	Orthic A	diffuse	fine	fine	crumb	Neocutanic B	diffuse	weak	fine	sub.ang blocky
7561	30	Ms 1100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	strong	fine	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	strong	medium	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	strong	medium	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	strong	medium	crumb	no sub horizon				
7561	30	Gs 1111	Orthic A	distinct	moderate	fine	crumb	Lithocutanic B	sharp	moderate	medium	sub.ang blocky
7561	30	Ms 1100	Orthic A	abrupt	moderate	medium	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	moderate	medium	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	strong	medium	crumb	no sub horizon				
7561	30	Gs 1111	Orthic A	abrupt	strong	medium	crumb	Lithocutanic B	sharp	strong	medium	sub.ang blocky
7561	30	Ms 1100	Orthic A	abrupt	weak	fine	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
7561	30	Ms 1100	Orthic A	abrupt	moderate	medium	crumb	no sub horizon				

Appendix 3.4. Field data collected for the 'slight decrease' sites.

				Topsoil				Subsoil				
Site name	**% change**	**Soil Form + Family**	**Horizon type**	**Horizon boundary**	**Structure (grade)**	**(size)**	**(class)**	**Horizon type**	**Horizon boundary**	**Structure (grade)**	**(size)**	**(class)**
9574	-9	Ms 1200	Orthic A	abrupt	moderate	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1200	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1100	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Ms 1100	Orthic A	abrupt	weak	medium	sub.ang blocky	no sub horizon				
9574	-9	Sw 1111	Orthic A	diffuse	weak	medium	sub.ang blocky	Pedocutanic B	abrupt	medium	medium	sub.ang blocky
9574	-9	Sw 1111	Orthic A	distinct	strong	medium	crumb	Pedocutanic B	distinct	strong	medium	blocky
9574	-9	Gs 1111	Orthic A	distinct	strong	medium	crumb	Lithocutanic B	distinct	moderate	medium	sub.ang blocky
9574	-9	Ms 2100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
9574	-9	Ms 2100	Orthic A	abrupt	moderate	fine	crumb	no sub horizon				
9574	-9	Gs 1111	Orthic A	distinct	weak	fine	granular	Lithocutanic B	distinct	strong	medium	sub.ang blocky
9574	-9	Ms 1100	Orthic A	abrupt	weak	medium	crumb	no sub horizon				
9574	-9	Ms 1100	Orthic A	abrupt	moderate	Fine	crumb	no sub horizon				

Appendix 3.4. (continued)

			Topsoil					Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)
9574	-9	Gs 1111	Orthic A	distinct	strong	fine	crumb	Lithocutanic B	distinct	moderate	medium	sub.ang blocky
9574	-9	My 1100	Melanic A	abrupt	moderate	medium	crumb	Lithocutanic B	distinct	moderate	medium	sub.ang blocky
8278	-12	Oa 2120	Orthic A	gradual	weak	fine	crumb	Neocutanic B	gradual	weak	fine	sub.ang blocky
8278	-12	Oa 2120	Orthic A	gradual	weak	fine	granular	Neocutanic B	gradual	weak	fine	sub.ang blocky
8278	-12	Oa 2120	Orthic A	abrupt	weak	fine	single grain	Neocutanic B	abrupt	weak	fine	sub.ang blocky
8278	-12	Sn 1000	Melanic A	gradual	moderate	medium	sub.ang blocky	Soft carbonate B	gradual	moderate	medium	sub.ang blocky
8278	-12	Sn 1000	Melanic A	gradual	moderate	medium	sub.ang blocky	Soft carbonate B	gradual	moderate	medium	sub.ang blocky
8278	-12	Oa 2120	Orthic A	gradual	weak	fine	granular	Neocutanic B	gradual	weak	fine	sub.ang blocky
8278	-12	Hu 3200	Orthic A	gradual	weak	fine	crumby	Red apedal.B	gradual	no struc	no struc	apedal
8278	-12	Hu 3200	Orthic A	gradual	weak	fine	crumb	Red apedal.B	gradual	no struc	no struc	apedal

Appendix 3.5. Field data collected for the 'slight decrease' sites.

				Topsoil				Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)
0991	-40	Se 1110	Orthic A	diffuse	moderate	fine	granular	Pedocutanic B	diffuse	moderate	fine	sub.ang blocky
0991	-40	Se 1110	Orthic A	diffuse	small	fine	sub.ang blocky	Pedocutanic B	sharp	small	fine	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	small	fine	sub.ang blocky	Pedocutanic B	gradual	small	fine	sub.ang blocky
0991	-40	Se 1110	Orthic A	diffuse	small	fine	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	fine-mod	medium	sub.ang blocky	Pedocutanic B	diffuse	coarse	medium	sub.ang blocky
0991	-40	Se 1110	Orthic A	diffuse	fine-mod	fine-med	sub.ang blocky	Pedocutanic B	diffuse	moderate	fine-med	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Se 1110	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Ka 2000	Orthic A	diffuse	fine	fine	fine sub.ang blocky	G	diffuse	moderate	medium	sub.ang blocky
0991	-40	Oa 1110	Orthic A	diffuse	moderate	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	granular
0991	-40	Oa 1110	Orthic A	diffuse	fine	fine	granular	Neocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Oa 1110	Orthic A	diffuse	fine	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Oa 1110	Orthic A	diffuse	fine	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Oa 1110	Orthic A	diffuse	fine	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	medium	granular
0991	-40	Tu 1110	Orthic A	diffuse	fine	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Tu 1110	Orthic A	diffuse	fine	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Oa 1110	Orthic A	diffuse	moderate	medium	sub.ang blocky	Neocutanic B	diffuse	moderate	fine	granular
0991	-40	Oa 1110	Orthic A	diffuse	moderate	medium	sub.ang blocky	Neocutanic B	diffuse	fine	fine	sub.ang blocky
0991	-40	Oa 1110	Orthic A	diffuse	moderate	fine	sub.ang blocky	Neocutanic B	diffuse	moderate	fine	granular

Appendix 3.5. (continued)

			Topsoil					Subsoil				
Site name	% change	Soil Form + Family	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)	Horizon type	Horizon boundary	Structure (grade)	(size)	(class)
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
0991	-40	Va 2111	Orthic A	diffuse	moderate	medium	sub.ang blocky	Pedocutanic B	diffuse	moderate	medium	sub.ang blocky
9985	-42	Ms 1100	Orthic A	abrubt	moderate	fine	crumb	hard rock				
9985	-42	Ms 1100	Orthic A	abrubt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrubt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	moderate	fine	crumb	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Oa 1120	Orthic A	diffuse	moderate	fine	crumb	Neocutanic B	distinct	strong	medium	sub.ang blocky
9985	-42	Se 1110	Orthic A	distinct	mod/strong	medium	crumb	Pedocutanic B	distinct	moderate	medium	sub.ang blocky
9985	-42	Se 1110	Orthic A	distinct	moderate	fine	crumb	Pedocutanic B	sharp	strong	medium	sub.ang blocky
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Ms 1100	Orthic A	abrupt	weak	fine	granular	hard rock				
9985	-42	Tu 1120	Orthic A	distinct	moderate	fine	crumb	Neocutanic B	distinct	v.strong	fine	sub.ang blocky
9985	-42	Tu 1120	Orthic A	distinct	strong	medium	crumb	Neocutanic B	distinct	v.strong	medium	sub.ang blocky

Appendix 3.5. (continued)

			Topsoil					Subsoil				
Site name	**% change**	**Soil Form + Family**	**Horizon type**	**Horizon boundary**	**Structure (grade)**	**(size)**	**(class)**	**Horizon type**	**Horizon boundary**	**Structure (grade)**	**(size)**	**(class)**
8376	-65	Ms 1100	Orthic A	abrupt	moderate	medium	sub.ang blocky	hard rock				
8376	-65	Sw 1111	Orthic A	gradual	coarse	coarse	blocky	Pedocutanic B	gradual	coarse	coarse	blocky
8376	-65	Va 1112	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Va 1112	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Pr 1110	Orthic A	gradual	moderate	medium	sub.ang blocky	Hardpan Carb	gradual	moderate	medium	sub.ang blocky
8376	-65	Sw 1111	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Dr 1000	Orthic A	abrupt	moderate	medium	sub.ang blocky	no sub horizon				
8376	-65	Sw 1111	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Gs 1112	Orthic A	gradual	coarse	coarse	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Sw 1111	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Va 1111	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky
8376	-65	Sw 1111	Orthic A	gradual	moderate	medium	sub.ang blocky	Pedocutanic B	gradual	moderate	medium	sub.ang blocky

Appendix 4: Munsell Colour and Colour Group (Munsell Color, 2000)

Appendix 4.1. Munsell colour and colour group for the ‘no-change’ sites

			Topsoil			Subsoil		
Site name	% change	Soil form + family	Munsell Colour (dry)	(moist)	Colour group	Munsell Colour (dry)	(moist)	Colour group
0894	4	Gs 1211	5YR 3/3	7.5YR 3/2	1	5YR 3/2	7.5YR 3/4	2
0894	4	Gs 1211	10YR 5/3	7.5YR 3/3	6	5YR 3/2	7.5YR 3/4	2
0894	4	Oa 1210	5YR 3/2	7.5YR 2.5/2	1	5YR 3/3	7.5YR 3/3	2
0894	4	Oa 1210	2.5YR 2.5/4	5YR 3/3	1	2.5YR 3/4	2.5YR 2.5/4	2
0894	4	Gs 1111	10YR 4/3	7.5YR 3/2	6	7.5YR 3/3	7.5YR 3/1	2
0894	4	Hu 2100	7.5YR 3/2	10YR 3/1	1	2.5 YR 4/6	2.5 YR 4/6	2
0894	4	Ms 2100	10YR 4/1	10YR 3/1	1	hard rock		
0894	4	My 1100	10YR 3/1	10YR 2/1	1	hard rock		
0894	4	Bo 1110	7.5YR 2.5/1	10YR 2/2	1	5YR 6/6	5YR 6/6	3
0894	4	Mw 1000	10YR 3/2	10YR 2/2	1	hard rock		
0894	4	Ms 1100	10YR 3/2	10YR 4/2	1	hard rock		
0894	4	Ms 1100	10YR 4/2	10YR 3/1	1	hard rock		
0894	4	Ms 1100	10YR 4/4	7.5YR 3/3	2	hard rock		
0894	4	Ms 1100	10YR 4/3	10YR 3/3	2	hard rock		
0894	4	Ms 1100	10YR 4/4	7.5YR 3/3	6	hard rock		
0894	4	Hu 2100	10YR 4/3	7.5YR 3/3	2	10YR 3/1	10YR 3/1	10
0894	4	Ms 1100	10YR 3/1	10YR 3/1	6	10YR 3/1	10YR 3/1	10
0894	4	Oa 1110	10YR 3/1	10YR 3/1	1	5YR 6/6	5YR 6/6	3
0894	4	Ms 1100	10YR 3/1	10YR 2/1	1	hard rock		
0894	4	Ms 1100	10YR 3/3	7.5YR 3/4	1	hard rock		
0894	4	Ms 1100	10YR 3/3	7.5YR 3/4	2	hard rock		
0894	4	Ms 1100	10YR 2/2	10YR 2/1	2	hard rock		
0894	4	Ms 1100	10YR 3/2	10YR 2/1	1	hard rock		
0894	4	Ms 1100	10YR 3/3	10YR 3/2	1	hard rock		
0894	4	Gs 1111	10YR 4/2	7.5YR 2.5/1	2	7.5YR 3/3	7.5YR 3/1	1
0894	4	Gs 1111	10YR 3/2	7.5YR 3/2	2	10YR 3/1	10YR 2/1	1
0894	4	My 2100	10YR 4/2	7.5YR 3/2	1	hard rock		
0894	4	Ms 2100	10YR 4/2	7.5YR 3/2	2	hard rock		
0894	4	Gs 1211	10YR 4/2	7.5YR 3/2	2	10YR 3/1	10YR 2.5/1	2
0894	4	Gs 1111	10YR 4/2	7.5YR 3/2	2	7.5YR 4/4	7.5YR 4/4	3
0894	4	Ms 1100	10YR 4/2	7.5YR 3/2	2	hard rock		
0894	4	Oa 1210	10YR 4/2	7.5YR 3/2	2	10YR 3/2	10YR 3/3	1
0894	4	Oa 1210	2.5YR 2.5/2	10YR 2/2	2	2.5YR 2.5/3	5YR 3/4	1
0894	4	Oa 1210	5YR 2.5/2	2.5YR 3/2	1	2.5YR 3/3	2.5YR 3/4	2
0894	4	Gs 1111	7.5YR 2.5/2	10YR 2/2	2	2.5YR 2.5/4	2.5YR 2.5/4	1

Appendix 4.1. (continued)

			Topsoil			Subsoil		
Site name	% change	Soil form + family	Munsell Colour (dry)	(moist)	Colour group	Munsell Colour (dry)	(moist)	Colour group
0894	4	Oa 1210	7.5YR 4/2	5YR 3/2	1	2.5YR 5/8	2.5YR 4/5	2
0894	4	Gs 1111	5YR 3/2	5YR 3/1	2	2.5YR 3/4	2.5YR 3/3	2
0894	4	Oa 1210	7.5YR 4/2	7.5YR 3/2	2	2.5YR 3/4	2.5YR 3/3	2
0894	4	Gs1111	7.5YR 3/2	7.5YR 3/2	2	2.5YR 3/4	2.5YR 3/3	2
0894	4	Gs1111	7.5YR 3/2	7.5YR 3/2	2	2.5YR 3/4	2.5YR 3/3	2
0898	2	Hu 2200	2.5YR 2.5/4	2.5YR 3/2	2	2.5YR 3/2	2.5YR 3/2	2
0898	2	Hu 1100	7.5YR 3/4	7.5YR 2.5/2	2	5YR 3/4	5YR 3/4	3
0898	2	Hu 1100	7.5YR 3/4	7.5YR 2.5/3	2	7.5YR 2.5/2	7.5YR 2.5/2	2
0898	2	Hu 1100	7.5YR 3/3	7.5YR 3/3	2	5YR 3/4	5YR 3/4	3
0898	2	Oa 1220	7.5YR 3/3	7.5YR 2.5/3	2	2.5YR 3/6	2.5YR 3/6	3
0898	2	Oa 1220	7.5YR 2.5/3	7.5YR 3/3	1	5YR 3/4	5YR 3/4	1
0898	2	Hu 2200	7.5 YR 3/4	7.5YR 3/4	2	5YR 4/4	5YR 4/6	1
0898	2	Hu 2200	7.5YR 3/2	7.5YR 4/4	2	5YR 3/4	5YR 3/4	1
0898	2	Sw 1111	10YR 3/4	10YR 2/2	2	7.5 YR 3/2	7.5YR 3/4	1
0898	2	Hu 2200	7.5YR 3/2	7.5YR 3/2	2	5YR 3/3	5YR 3/4	2
0898	2	Sw 1111	7.5YR 3/4	7.5YR 3/2	2	5YR 3/3	5YR 3/3	2
0898	2	Cv 2100	10YR 2/2	10YR 3/2	1	10YR 3/3	10YR 3/2	2
0898	2	Hu 3100	7.5YR 3/3	7.5YR 2.5/2	2	2.5YR 3/4	2.5YR 3/6	2
0898	2	Hu 3100	7.5YR 2/3	7.5YR 2.5/2	1	2.5YR 3/4	2.5YR 3/6	2
0898	2	Hu 3100	7.5YR 3/2	7.5YR 2.5/2	2	2.5YR 3/4	2.5YR 3/6	2
0898	2	Oa 1210	7.5YR 3/2	7.5YR 2.5/2	2	5YR 3/3	5YR 3/4	2
0898	2	Oa 1210	7.5YR 3/2	7.5YR 3/3	2	5YR 3/3	5YR 3/4	2
0898	2	Hu 2200	3.5YR 3/2	7.5YR 2.5/3	1	10YR 3/6	5YR 3/4	2
0898	2	Hu 2200	5YR 3/2	2.5YR 3/3	1	2.5YR 3/6	10YR 3/4	2
0898	2	Hu 2200	2.5YR 3/4	2.5YR 3/3	1	2.5YR 3/6	10YR 3/4	2
0898	2	Sw 1111	5YR 3/3	7.5YR 2.5/2	1	2.5YR 3/6	10YR 3/4	2
0898	2	Oa 1210	10YR 3/2	10YR 3/2	1	2.5YR 3/6	10YR 3/4	2
9570	4	Bo 1120	2.5YR 3/1	10YR 2/1	2	7.5YR 4/4	10YR 4/3	2
9570	4	Bo 1120	10YR 3/2	10YR 2/1	1	10YR 3/3	10YR 4/3	2
9570	4	My 1200	5YR 3/1	5YR 2.5/1	1	10YR 3/3	10YR 4/3	2
9570	4	Ms 1100	10YR 3/2	10YR 2/1	1	hard rock		
9570	4	Ms 1100	10YR 4/2	10YR 4/4	2	hard rock		
9570	4	Bo 1110	10YR 3/2	10YR 2/1	1	10YR 4/2	10YR 4/4	2
9570	4	Ik 1100	10YR 3/2	10YR 2/1	1	2.5YR 3/6	10YR 3/4	2
9570	4	Bo 1110	7.5YR 2.5/1	10YR 2/1	1	10YR 4/2	10YR 4/4	2
9570	4	Bo 1110	10YR 4/3	10YR 2/2	2	7.5YR2.5/2	7.5YR 2.5/2	1
9570	4	Bo 1110	7.5YR2.5/1	7.5YR 1/1	1	5YR 3/3	5YR 3/1	2

Appendix 4.1. (continued)

			Topsoil			Subsoil		
Site name	% change	Soil form + family	Munsell Colour (dry)	(moist)	Colour group	Munsell Colour (dry)	(moist)	Colour group
9570	4	Bo 1110	10YR 3/1	7.5YR 2.5/1	1	7.5YR 2/1	7.5YR 3/1	1
9570	4	Bo 1110	10 YR 2/1	10YR 2/1	1	10YR 2/1	7.5YR 2.5/2	1
9570	4	Bo 1110	7.5YR 3/2	7.5YR 2.5/1	2	5YR 3/3	5YR 3/2	2
9570	4	Va 1211	5YR 3/2	5YR 3/2	2	5YR 3/1	5YR 3/3	1
9570	4	Ms 1100	7.5YR 3/2	7.5YR 2.5/1	2	hard rock		
9570	4	Bo 1110	10YR 3/2		1	7.5YR 3/3	7.5YR 3/3	1
9570	4	Bo 1110	7.5YR 3/2	7.5YR 2.5/1	2	7.5YR 3/3	7.5YR 3/3	1
9570	4	Ar 1100	7.5YR 2.5/1	7.5YR 3/1	1	no subsoil		
9570	4	Rg 2000	7.5YR 4/2	7.5YR 2.5/1	3	5YR 3/1	5YR 3/2	1
9570	4	Rg 2000	7.5YR 2.5/1	7.5YR 2.5/1	1	5YR 3/1	5YR 3/2	2
9570	4	Ar 1100	7.5YR 2.5/1	7.5YR 2.5/1	1	no subsoil		
9570	4	Bo 1100	7.5YR 3/2	7.5YR 3/1	2	7.5YR 3/2	7.5YR 3/1	2
9570	4	Ms 1100	7.5YR 4/2	7.5YR 3/2	3	hard rock		
9570	4	Ms 1100	5YR 3/2	7.5YR 3/2	2	hard rock		
9570	4	Bo 1100	7.5YR 3/1	7.5YR 3/2	1	7.5YR 3/1	7.5YR 3/2	2
9570	4	Rg 2000	7.5YR 3/2	7.5YR 2.5/1	2	5YR 3/2	5YR 3/3	2
9570	4	Bo 1110	7.5YR 3/2	7.5YR 3/1	2	7.5YR 3/2	7.5YR 3/2	2
8168	3	Ms 1100	10YR 5/2	7.5YR 2.5/1	6	hard rock		
8168	3	Ms 1100	10YR 4/1	10YR 2/1	1	hard rock		
8168	3	Sw 1111	10R 5/3	10YR 3/2	6	7.5YR 3/2	7.5YR 3/2	2
8168	3	Sw 1111	10YR 5/2	7.5YR 3/1	6	7.5YR 3/2	7.5YR 3/2	2
8168	3	Ms 1100	10YR 2/1	10YR 4/2	1	hard rock		
8168	3	Ms 1100	10YR 2/1	10YR 2/1	1	hard rock		
8168	3	Ms 1100	10YR 3/2	10YR 3/1	1	hard rock		
8168	3	Ms 1100	10YR 2/1	10YR 2/2	1	hard rock		
8168	3	Mw 1100	10YR 2/1	10YR 2/1	1	hard rock		
8168	3	Ms 1100	7.5YR 5/2	10YR 3/1	6	hard rock		
8168	3	Ms 1100	10YR 3/3	10YR 3/1	2	hard rock		
8168	3	Ms 2100	10YR 2/1	10YR 3/3	1	hard rock		
8168	3	Sw 1111	10YR 4/4	10YR 3/3	2	10YR 4/4	10YR 4/3	2
8168	3	Ms 1100	7.5YR3/3	7.5YR 3/2	2	hard rock		
8168	3	Ms 2100	7.5YR 3/1	10YR 2/1	1	hard rock		
8168	3	Ms 1100	10YR 3/1	10YR 2/1	1	hard rock		
8168	3	Sw 1111	10YR 4/1	10YR 2/1	1	7.5YR 3/2	7.5YR 3/2	2
8168	3	Ms 2100	10YR 3/2	10YR 2/1	1	hard rock		
8168	3	Ms 1100	10YR 3/2	10YR 2/1	1	hard rock		
8168	3	Ms 1100	10YR 3/1	10YR 2/1	1	hard rock		
8168	3	Sw 1111	7.5YR 5/2	10YR 3/2	2	10YR 3/3	10YR 2/2	2

Appendix 4.1. (continued)

			Topsoil			Subsoil		
Site name	% change	Soil form + family	Munsell Colour (dry)	(moist)	Colour group	Munsell Colour (dry)	(moist)	Colour group
8168	3	Sw 2111	10YR 3/2	10YR 2/1	1	7.5YR 3/4	7.5YR 3/4	2
8168	3	Sw 2111	7.5YR 3/2	7.5YR 3/2	2	10YR 3/2	10YR 2/2	1
8168	3	Sw 2111	7.5YR 2.5/1	10YR 2/1	1	10YR 3/2	10YR 2/1	1
8168	3	Sw 2111	10YR 3/2	10YR 2/2	1	10YR 3/2	10YR 2/1	1
8168	3	Ms 1100	10YR 3/1	10YR 2/1	1	hard rock		
8168	3	Sw 2111	10YR 3/2	10YR 2/1	1	7.5YR 3/2	7.5YR 3/4	2
8168	3	Ms 1100	10YR 3/1	10YR 3/1	1	hard rock		
8168	3	Ms 1100	10YR 3/1	10YR 2/1	1	hard rock		

Appendix 4.2. Munsell colour and colour group for the 'slight increase' in tree density sites

			Topsoil			Subsoil		
Site name	**% change**	**Soil form + family**	**Munsell Colour (dry)**	**(moist)**	**Colour group**	**Munsell Colour (dry)**	**(moist)**	**Colour group**
9782	10	Km 1110	10YR 5/3	7.5YR 4/3	2	10YR 4/2	10YR 4/2	2
9782	10	Tu 1110	10YR 5/3	10YR 4/3	2	2.5Y 3/3	2.5Y 3/3	2
9782	10	Ms 1100	10YR 4/2	10YR 3/2	2	hard rock		
9782	10	Ar 1100	10YR 3/2	10YR 2/4	2	10YR 5/4	10YR 5/4	2
9782	10	Ik 2100	7.5YR 2.5/1	10YR 3/1	1	10YR 5/4	10YR 5/4	2
9782	10	Ar 1100	10YR 3/2	10YR 3/1	1	10YR 6/6	10YR 6/6	2
9782	10	Bo 1110	10YR 3/1	10YR 3/2	1	hard rock		
9782	10	Ms 1100	2.5Y 3/2	2.5Y 4/3	1	hard rock		
9782	10	Ms 2100	2.5Y 3/2	2.5Y 3/2	1	hard rock		
9782	10	Gs 2121	2.5Y 5/2	2.5Y 4/2	6	no sub horizon		
9782	10	Gs 2121	2.5Y 5/2	2.5Y 4/2	6	no sub horizon		
9782	10	Ms 2100	2.5Y 5/2	2.5Y 3/2	6	hard rock		
9782	10	Ms 1100	2.5Y 3/2	2.5Y 3/1	1	hard rock		
9782	10	Ar 1100	2.5Y 3/2	2.5Y 2.5/1	1	no sub horizon		
9782	10	Ms 1100	10 YR 3/2	10YR 4/3	1	hard rock		
9782	10	My 1100	10YR 3/1	10YR 3/1	1	hard rock		
9782	10	Ar 1100	10YR 3/2	7.5YR 3/1	1	no sub horizon		
9782	10	Ms 2100	2.5Y 5/2	2.5Y 3/2	6	hard rock		
9782	10	Ms 2100	2.5Y 5/2	2.5Y 3/2	6	hard rock		
0479	13	Gs 1111	10YR 4/2	7.5YR 3/1	2	2.5Y 4/3	2.5Y 4/3	2
0479	13	Oa 1000	10YR 4/2	7.5YR 3/2	2	2.5Y 3/2	2.5Y 3/2	2
0479	13	Se 2210	2.5Y 4/1	5YR 2.5/1	6	2.5Y 4/3	2.5Y 4/3	1
0479	13	Oa 1000	10YR 4/2	7.5YR 3/1	2	10YR 4/2	10YR 4/2	1
0479	13	Vf 1110	10YR 3/2	10YR 3/1	1	2.5Y 3/3	2.5Y 3/3	2
0479	13	Fw	5YR 3/1	10YR 2/1	1	hard rock		
0479	13	Gs 1111	10YR 3/2	10YR 3/1	1	10YR 4/6	10YR 4/6	1
0479	13	Gs 1111	2.5Y 3/2	7.5YR 2.5/1	1	hard rock		
0479	13	Gs 1111	2.5Y3/2	10YR 3/1	1	hard rock		
0479	13	Vf 1110	2.5Y 3/2	10YR 3/1	1	2.5Y 3/3	2.5Y 3/3	2

Appendix 4.3. Munsell colour and colour group for the 'increase' in tree density sites

			Topsoil			Subsoil		
Site name	% change	Soil form + family	Munsell Colour (dry)	(moist)	Colour group	Munsell Colour (dry)	(moist)	Colour group
0994	35	Sw 1111	2.5YR 3/2	2.5YR 2.5/2	1	2.5YR 3/3	2.5YR 3/3	1
0994	35	Hu 2100	2.5YR 2.5/2	5YR 3/3	1	2.5YR 3/6	2.5YR 3/6	2
0994	35	Sw 1111	2.5YR 3/2	2.5YR 2.5/2	1	2.5YR 4/6	2.5YR 4/6	3
0994	35	Ms 1100	5YR 3/3	5YR 3/3	2	hard rock		
0994	35	Sw 1111	2.5YR 3/2	2.5YR 3/2	1	2.5YR 3/4	2.5YR 3/4	3
0994	35	Ms 1100	2.5YR 3/1	5YR 3/1	2	hard rock		
0994	35	Gs 1211	5YR 2.5/2	5YR 2.5/1	1	10YR 4/2	10YR 4/3	2
0994	35	Ms 1100	2.5YR 3/1	2.5YR 2.5/2	1	hard rock		
0994	35	Sw 1111	2.5YR 2.5/2	2.5YR 2.5/1	1	2.5YR 2.5/2	2.5YR 2.5/1	2
0994	35	Oa 1110	2.5YR 2.5/2	2.5YR 2.5/2	1	2.5YR 2.5/2	2.5YR 3/3	1
0994	35	Ms 1100	2.5YR 2.5/1	2.5YR 2.5/2	1	hard rock		
0994	35	Va 2111	2.5YR 2.5/1	2.5YR 2.5/2	1	2.5YR 3/4	2.5YR 3/3	1
0994	35	Hu 2100	2.5YR 2.5/2	2.5YR 2.5/2	1	2.5YR 3/6	2.5YR 3/6	2
9579	47	Sw 1121	10YR 3/2	10YR 3/1	1	10YR 4/3	7.5YR 3/2	2
9579	47	Sw 1121	10YR 4/1	10YR 3/1	1	10YR 3/2	10YR 3/2	1
9579	47	Sw 1121	7.5YR 3/1	10YR 3/1	1	7.5YR 3/1	7.5YR 3/1	1
9579	47	Sw 1121	7.5YR 4/1	10YR 2/1	1	7.5YR 3/1	10YR 2/1	1
9579	47	Sw 1111	10YR 3/1	7.5YR 2.5/1	1	7.5YR 3/2	7.5YR 3/3	2
9579	47	Sw 1111	7.5YR 3/1	7.5YR 2.5/1	1	7.5YR 3/2	7.5YR 3/3	2
9579	47	Sw 1211	10YR 3/1	7.5YR 2.5/1	1	10YR 1/2	10YR 2/1	1
9579	47	Oa 1110	7.5 YR 4/1	7.5YR 3/2	1	7.5YR 3/1	7.5YR 4/2	1
9579	47	Oa 1110	10YR 3/2	7.5YR 3/1	1	7.5YR 3/1	7.5YR 4/2	1
9579	47	Fw 1110	10YR 4/2	10YR 3/2	2	10YR 4/2	10YR 4/2	2
9579	47	Oa 1110	10YR 4/1	10YR 3/2	1	10YR 1/3	10YR 4/3	1
7561	30	Ms 1100	10YR 3/4	5YR 3/2	2	hard rock		
7561	30	Ms 1100	7.5YR 3/3	5YR 3/2	2	hard rock		
7561	30	Ms 1100	7.5YR 3/3	5YR 3/2	2	hard rock		
7561	30	Ms 1100	7.5YR 3/2	5YR 3/2	2	hard rock		
7561	30	Ms 1100	7.5YR 4/6	2.5YR 5/3	10	hard rock		
7561	30	Ms 1100	10YR 3/3	10YR 2/2	2	hard rock		
7561	30	Gs 1111	10YR 3/4	5YR 3/2	2	10YR 5/3	10YR 5/3	2
7561	30	Ms 1100	10YR 3/3	7.5YR 3/2	2	hard rock		
7561	30	Ms 1100	10YR 3/4	5YR 3/3	2	hard rock		
7561	30	Ms 1100	5YR 4/3	2.5YR 3/2	3	hard rock		
7561	30	Gs 1111	10YR 3/4	7.5YR 3/3	2	10YR 5/3	10YR 5/3	2
7561	30	Ms 1100	7.5YR 4/6	7.5YR 4/6	10	hard rock		
7561	30	Ms 1100	7.5YR 3/3	5YR 3/3	2	hard rock		

7561	30	Ms 1100	7.5YR 3/4	5YR 3/3	2	hard rock		
7561	30	Ms 1100	10YR 3/3	10YR 3/2	2	hard rock		

Appendix 4.4. Munsell colour and colour group for the 'slight decrease' in tree density sites

			Topsoil			Subsoil		
Site name	**% change**	**Soil form + family**	**Munsell Colour (dry)**	**(moist)**	**Colour group**	**Munsell Colour (dry)**	**(moist)**	**Colour group**
9574	-9	Ms 1200	7.5YR 4/2	7.5YR 3/2	2	hard rock		
9574	-9	Ms 1200	10YR 3/3	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	10YR 3/3	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	10YR 4/5	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	10YR 4/5	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	10YR 3/3	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	7.5YR 2.5/4	10YR 3/3	1	hard rock		
9574	-9	Ms 1200	7.5YR 3/4	10YR 3/3	2	hard rock		
9574	-9	Ms 1200	10YR 3/3	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	10YR 3/3	7.5YR 3/3	2	hard rock		
9574	-9	Ms 1200	7.5YR 3/3	10YR 3/3	2	hard rock		
9574	-9	Ms 1200	7.5YR 3/3	10YR 3/3	2	hard rock		
9574	-9	Ms 1200	7.5YR 3/3	10YR 3/3	2	hard rock		
9574	-9	Ms 1100	10YR 2/2	7.5YR 3/3	1	hard rock		
9574	-9	Ms 1100	10YR 3/1	7.5YR 3/3	1	hard rock		
9574	-9	Sw 1111	10YR 4/3		2	7.5YR 2/1	7.5YR 2/1	1
9574	-9	Sw 1111	10YR 4/2	10YR 3/2	2	10YR 4/2	7.5YR 3/2	2
9574	-9	Gs 1111	10YR 3/1	7.5YR 3/2	1	10YR 3/2	10YR 3/2	2
9574	-9	Ms 2100	10YR 4/2	10YR 4/1	2	hard rock		
9574	-9	Ms 2100	10YR 5/2	10YR 5/2	6	hard rock		
9574	-9	Gs 1111	10YR 3/3	10YR 3/3	2	10YR 3/2	10YR 3/2	2
9574	-9	Ms 1100	10YR 4/3	10YR 3/1	2	hard rock		
9574	-9	Ms 1100	10YR 3/2	10YR 4/3	1	hard rock		
9574	-9	Gs 1111	10YR 3/2	10YR 3/2	1	7.5YR 3/2	7.5YR 3/2	2
9574	-9	My 1100	10YR 3/1	10YR 2/1	1	10YR 3/1	10YR 3/1	1
8278	-12	Oa 2120	7.5YR 4/3	10YR 3/2	2	10YR 4/4	10YR 4/4	2
8278	-12	Oa 2120	10YR 5/6	10YR 4/3	10	10YR 4/4	10YR 3/3	1
8278	-12	Oa 2120	10YR 6/8	10YR 4/4	10	10YR 3/2	10YR 4/1	2
8278	-12	Sn 1000	10YR 5/3	10YR 3/1	2	10YR 4/2	7.5YR 3/1	1
8278	-12	Sn 1000	10YR 5/4	10YR 3/3	2	2.5Y 3/1	2.5YR 4/1	1
8278	-12	Oa 2120	10YR 4/4	10YR 3/3	2	10YR 2/2	10YR 2/1	10
8278	-12	Hu 3200	5YR 4/2	5YR 3/3	2	5YR 3/4	2.5YR 2.5/3	10
8278	-12	Hu 3200	7.5YR 4/6	7.5YR 3/3	10	5YR 4/6	5YR 3/3	1

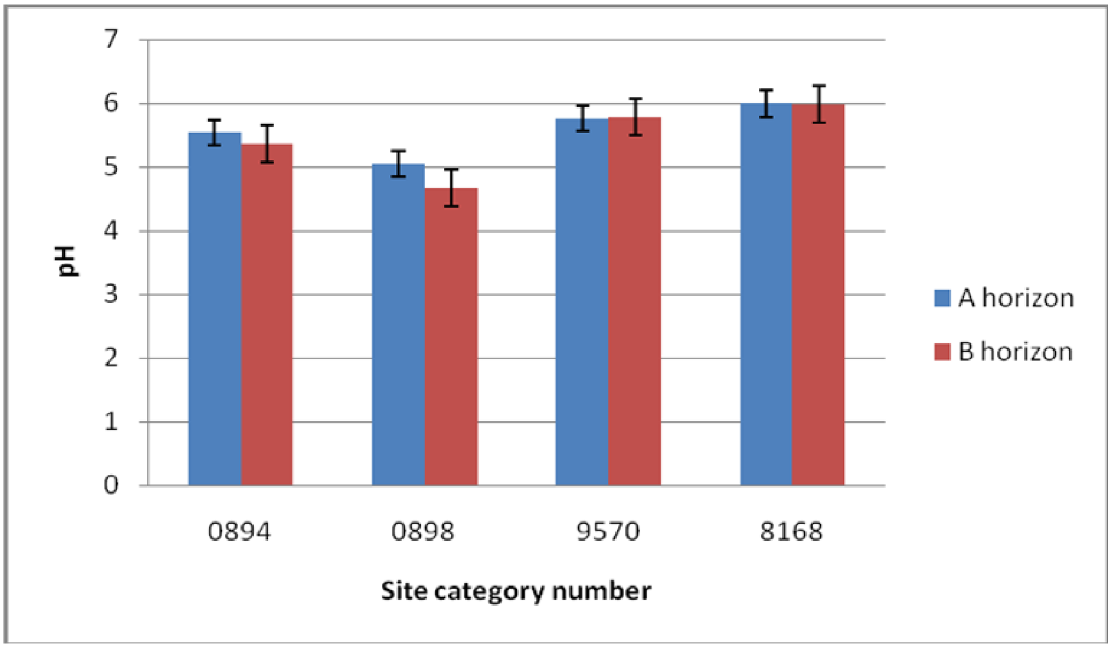
Appendix 4.5. Munsell colour and colour group for the 'decrease' in tree density sites

			Topsoil			Subsoil		
Site name	**% change**	**Soil form + family**	**Munsell Colour (dry)**	**(moist)**	**Colour group**	**Munsell Colour (dry)**	**(moist)**	**Colour group**
9985	-42	Ms 1100	10YR3/2	10YR3/1	1	hard rock		
9985	-42	Ms 1100	2.5Y 4/3	2.5Y 3/3	2	hard rock		
9985	-42	Ms 1100	2.5Y 4/2	10YR 3/2	2	hard rock		
9985	-42	Ms 1100	2.5Y 3/2	2.5Y 3/2	1	hard rock		
9985	-42	Ms 1100	2.5Y 4/3	2.5Y 3/2	2	hard rock		
9985	-42	Oa 1120	10YR 3/2	2.5Y 2.5/1	1	10YR 4/4	10YR 4/4	2
9985	-42	Se 1110	2.5Y 4/2	2.5Y 3/2	2	7.5YR 3/2	7.5YR 3/2	2
9985	-42	Se 1110	2.5Y 4/3	10YR 2/2	2	7.5YR 2.5/1	7.5YR 2.5/1	2
9985	-42	Ms 1100	10YR 3/1	5YR 3/1	1	2.5Y 3/2	2.5Y 3/2	
9985	-42	Ms 1100	10YR 4/1	7.5YR 3/1	1	hard rock		
9985	-42	Ms 1100	10YR 4/2	10YR 3/2	2	hard rock		
9985	-42	Ms 1100	2.5Y 5/3	2.5Y 3/2	9	hard rock		
9985	-42	Ms 1100	2.5Y 4/2	10YR 3/2	2	hard rock		
9985	-42	Ms 1100	2.5Y 4/3	2.5Y 3/2	2	hard rock		
9985	-42	Tu 1120	10YR 3/2	5YR 2.5/1	1	2.5Y 3/2	2.5Y 3/2	2
9985	-42	Tu 1120	5YR 3/1	7.5YR 3/1	1	7.5YR 2.5/1	7.5YR 2.5/1	1
8376	-65	Ms 1100	5YR 3/1	5YR 2.5/1	1	hard rock		
8376	-65	Sw 1111	5YR 3/1	5YR 2.5/1	1	7.5YR 4/1	7.5YR 3/1	1
8376	-65	Va 1112	7.5YR 3/1	7.5YR 3/1	1	7.5YR 4/1	7.5YR 3/1	1
8376	-65	Va 1112	7.5YR 3/2	7.5YR 3/1	2	7.5YR 4/1	7.5YR 3/1	2
8376	-65	Pr 1110	7.5YR 5/2	7.5YR 4/1	2	7.5YR 3/2	7.5YR 3/1	2
8376	-65	Sw 1111	7.5YR 3/1	7.5YR 3/2	1	7.5YR 3/2	7.5YR 3/1	2
8376	-65	Dr 1000	7.5YR3/2	7.5YR3/2	2	no sub horizon		
8376	-65	Sw 1111	7.5YR 3/2	7.5YR 3/1	2	7.5YR 3/2	7.5YR 3/1	2
8376	-65	Gs 1112	7.5YR 3/2	7.5YR 3/1	2	10YR 5/3	10YR 4/3	1
8376	-65	Sw 1111	7.5YR 3/2	7.5YR 3/1	2	7.5YR 3/1	7.5YR 2.5/1	1
8376	-65	Va 1111	7.5YR 3/1	7.5YR 3/2	1	7.5YR 4/1	7.5YR 3/2	1
8376	-65	Sw 1111	7.5YR 3/1	7.5 YR 3/2	1	7.5YR 3/1	7.5 YR 3/2	1
0991	-40	Se 1110	7.5YR 2.5/1	10YR 2/2	1	7.5YR 2.5/1	10YR 3/1	3
0991	-40	Se 1110	7.5YR 2.5/1	10YR 3/1	1	7.5YR 2.5/1	10YR 3/1	1
0991	-40	Va 2111	10YR 3/1	10YR 3/1	1	7.5YR 3/1	10YR 3/1	1
0991	-40	Se 1110	7.5YR 2.5/1	10YR 3/1	1	10YR 3/1	10YR 3/1	1
0991	-40	Va 2111	10YR 3/2	10YR 2/1	1	10YR 3/2	10YR 3/1	1
0991	-40	Se 1110	10YR 3/2	10YR 3/1	1	10YR 3/2	10YR 3/2	1
0991	-40	Va 2111	10YR 3/1	10YR 3/1	1	10YR 3/2	10YR 3/2	1

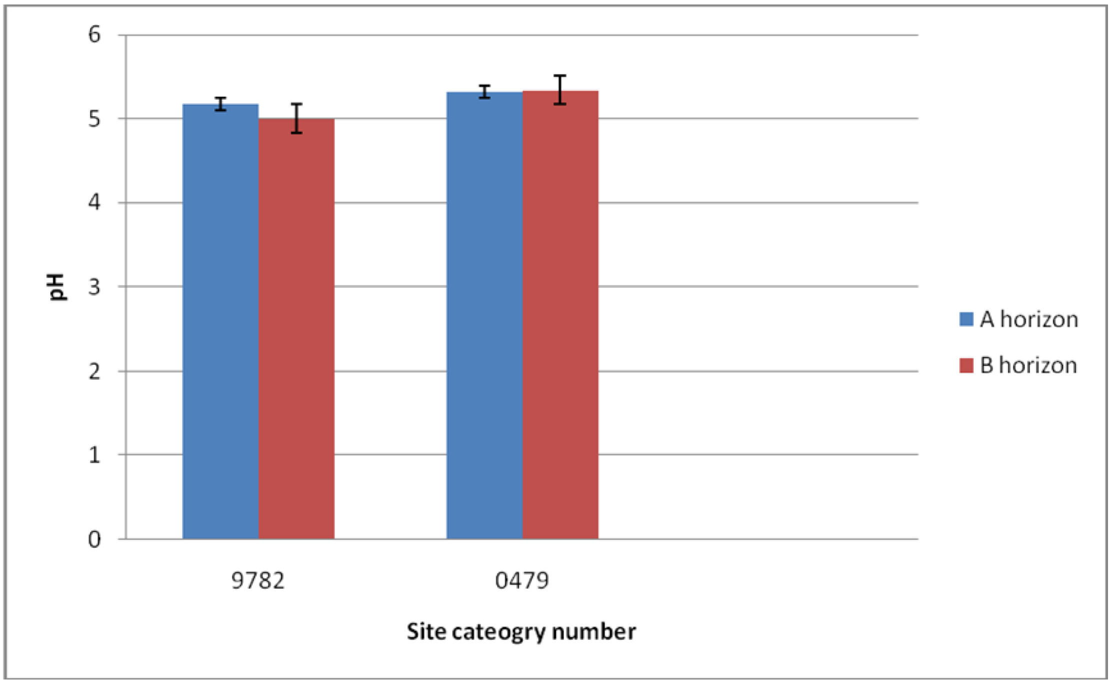
Appendix 4.5. (continued)

			Topsoil			Subsoil		
Site name	% change	Soil form + family	Munsell Colour (dry)	(moist)	Colour group	Munsell Colour (dry)	(moist)	Colour group
0991	-40	Se 1110	10YR 3/2	10YR 3/1	1	10YR 3/2	10YR 3/2	1
0991	-40	Ka 2000	7.5YR 4/1	7.5YR 3/2	1	7.5YR 4/2	7.5YR 3/2	1
0991	-40	Oa 1110	10YR 10/2	10YR 3/2	1	10YR 4/4	10YR 4/4	2
0991	-40	Va 2111	10YR 3/2	10YR2/1	1	10YR 4/3	10YR 3/2	1
0991	-40	Oa 1110	10YR 4/1	10YR 3/2	1	10YR 3/2	5YR 3/1	2
0991	-40	Oa 1110	10YR 4/1	10YR 2/1	1	10YR 3/2	10YR 3/1	1
0991	-40	Oa 1110	10YR 4/1	10YR 2/1	1	10YR 4/2	10YR 2/1	1
0991	-40	Oa 1110	10YR 4/2	10YR 2/2	2	10YR 4/2	10YR 2/2	2
0991	-40	Tu 1110	10YR 4/2	10YR 3/2	2	10YR 4/2	10YR 3/2	2
0991	-40	Tu 1110	10YR 4/2	10YR 3/2	2	10YR 3/1	10YR 3/2	2
0991	-40	Va 2111	10YR 4/2	10YR 3/2	2	10YR 4/1	7.5YR 3/2	1
0991	-40	Oa 1110	10YR 3/2	10YR 2/2	1	10YR 4/2	10YR 3/2	1
0991	-40	Oa 1110	10YR 4/2	10YR 2/2	2	10YR 4/2	10YR 3/2	2
0991	-40	Oa 1110	10YR 3/2	10YR 2/2	1	10YR 4/2	10YR 3/2	2
0991	-40	Va 2111	10YR 3/2	10YR 2/2	1	10YR 3/1	10YR 2/2	2
0991	-40	Va 2111	10YR 3/1	10YR 2/2	1	10YR 3/2	10YR 3/1	1
0991	-40	Va 2111	10YR 3/2	10YR 2/2	1	10YR 4/2	10YR 3/2	1
0991	-40	Va 2111	10YR 4/2	10YR 2/2	2	10YR 3/3	10YR 3/4	2
0991	-40	Va 2111	10YR 3/2	10YR 2/2	1	10YR 3/2	10YR 2/2	2
0991	-40	Va 2111	10YR 3/2	10YR 2/2	1	10YR 3/2	10YR 2/2	1
0991	-40	Va 2111	10YR 3/2	10YR 2/2	1	10YR 3/2	10YR 3/1	1

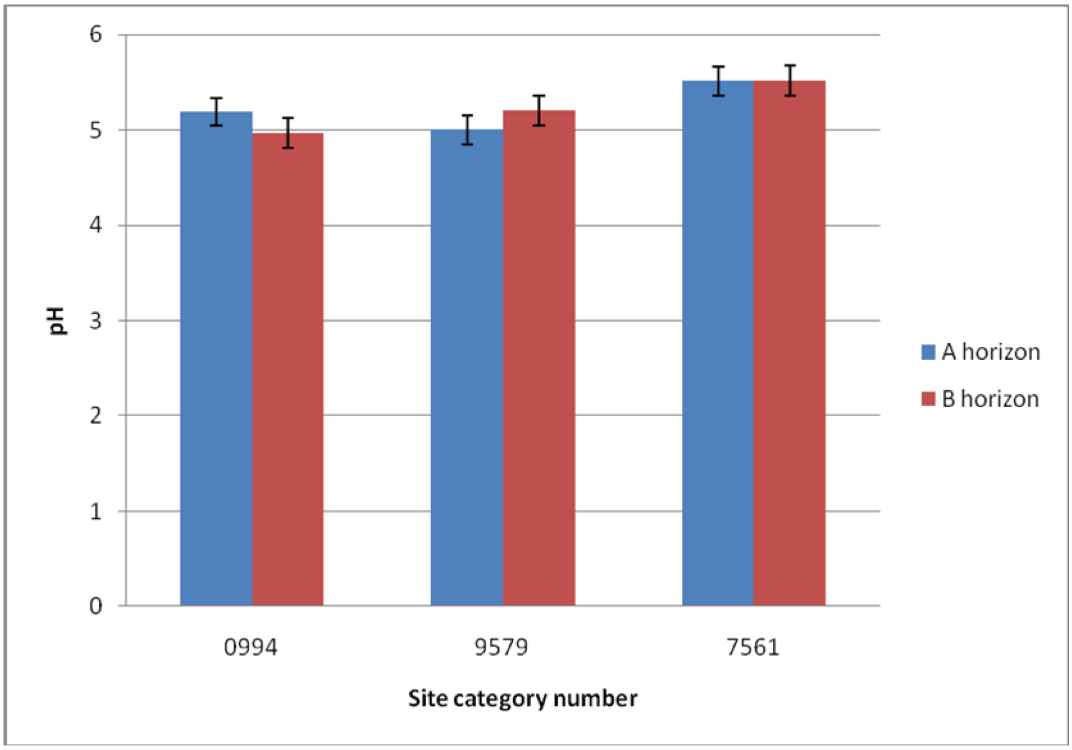
Appendix 5. Averages of the various laboratory results for the different sites.



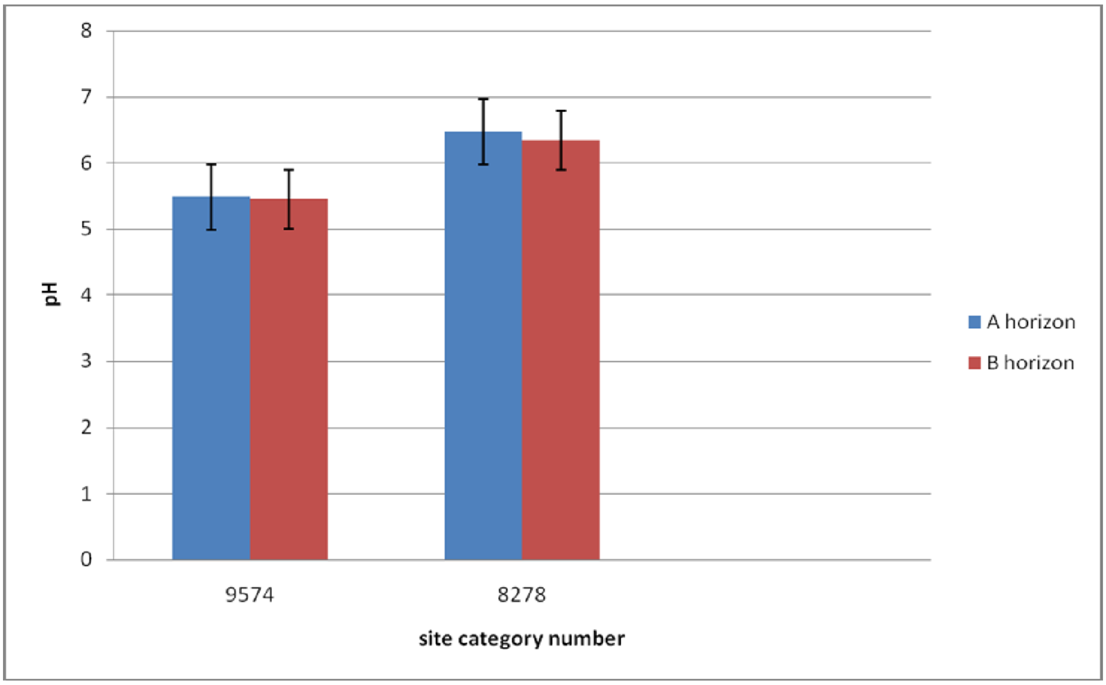
Appendix 5.1. Means of the pH (H_2O) of the samples analysed from the topsoil and subsoil of the 'no change' sites



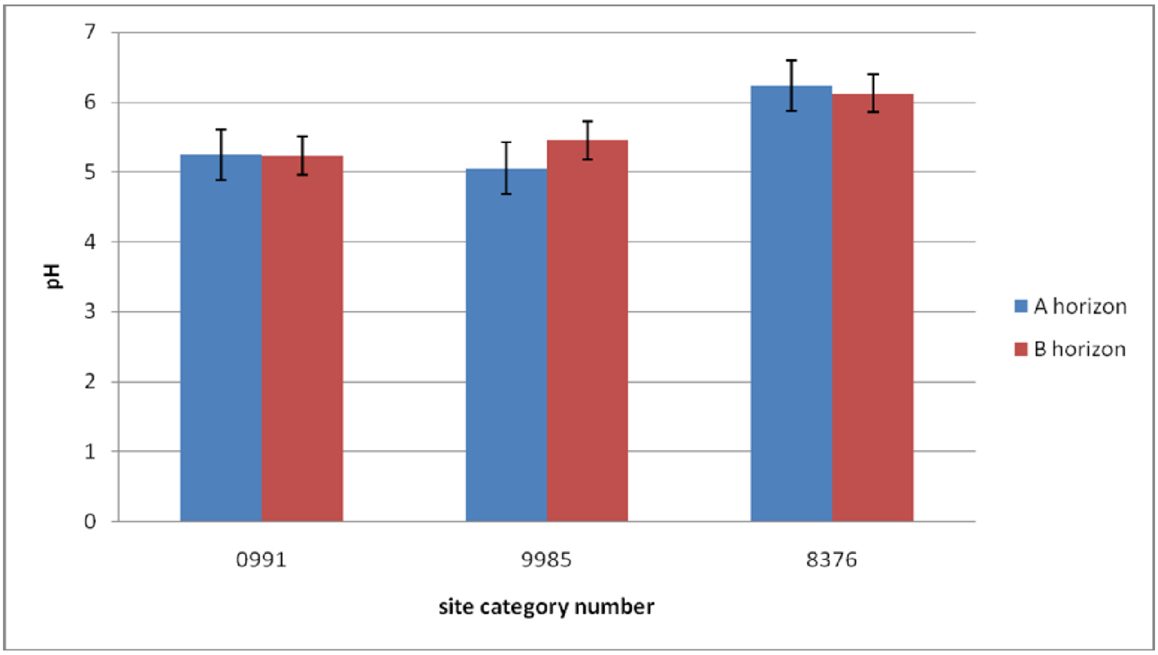
Appendix 5.2. Means of the pH (H_2O) of the samples analysed from the topsoil and subsoil of the 'slight increase' sites



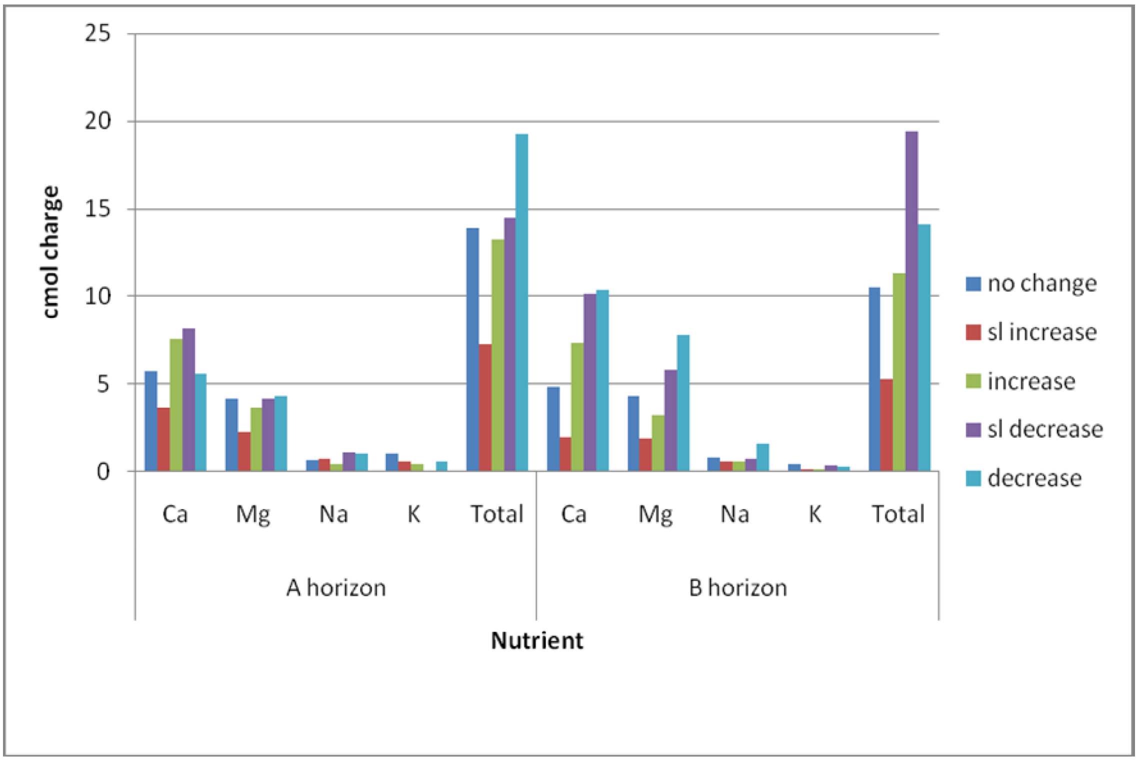
Appendix 5.3. Means of the pH (H_2O) of the samples analysed from the topsoil and subsoil of the 'increase' sites



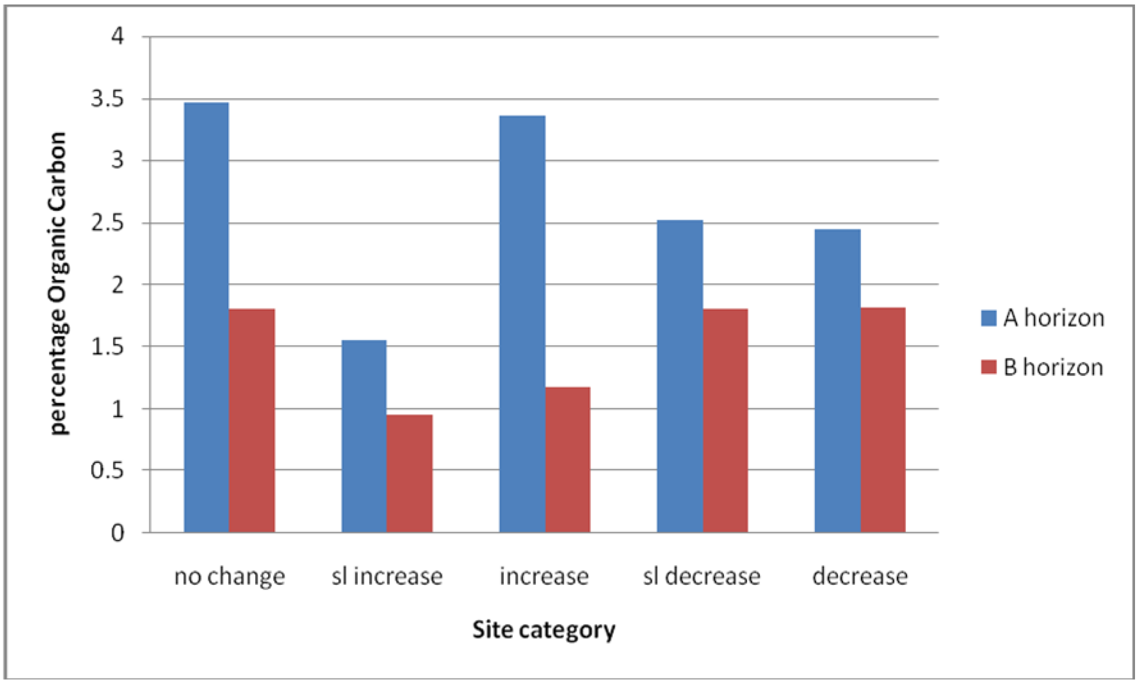
Appendix 5.4. Means of the pH (H_2O) of the samples analysed from the A and B horizons of the 'slight decrease' sites



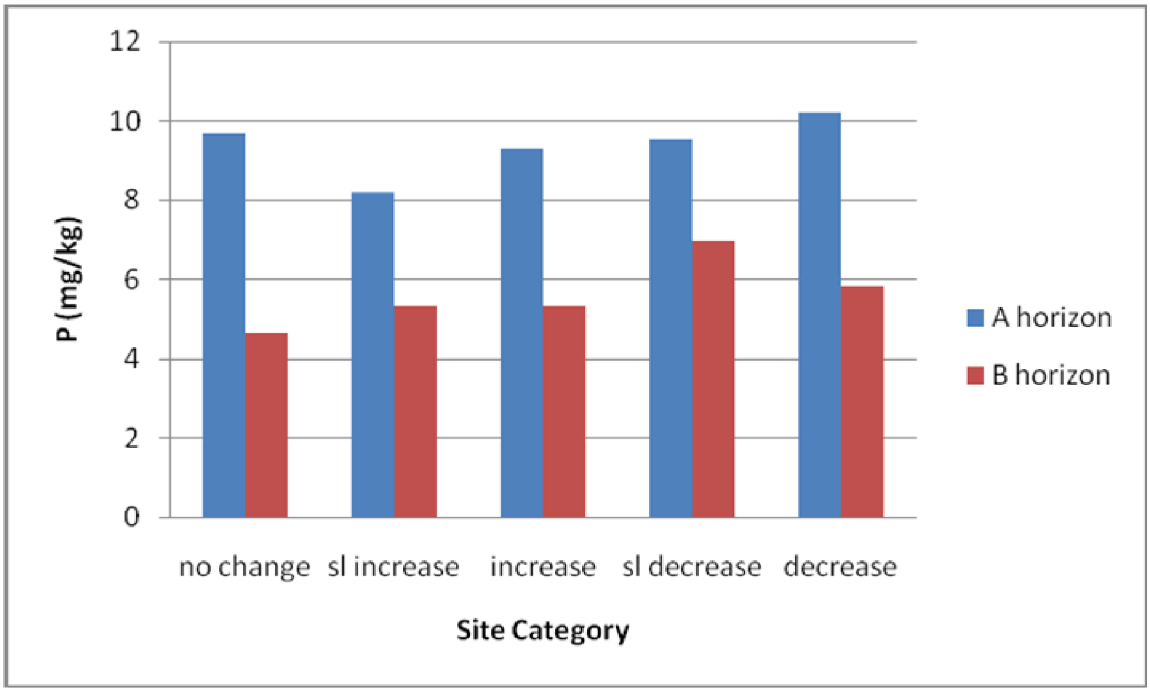
Appendix 5.5. Means of the pH (H_20) of the samples analysed from the A and B horizons of the 'decrease' sites



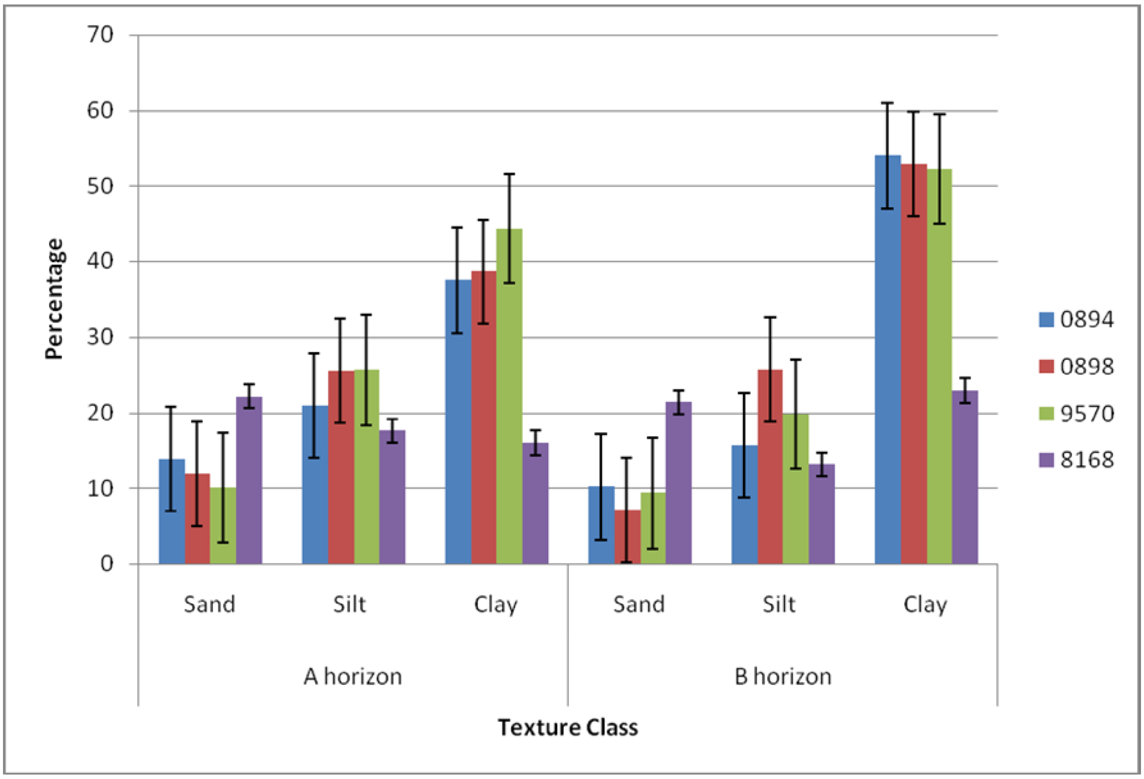
Appendix 5.6. Means of the nutrients tested in the laboratory for the various vegetation change classes



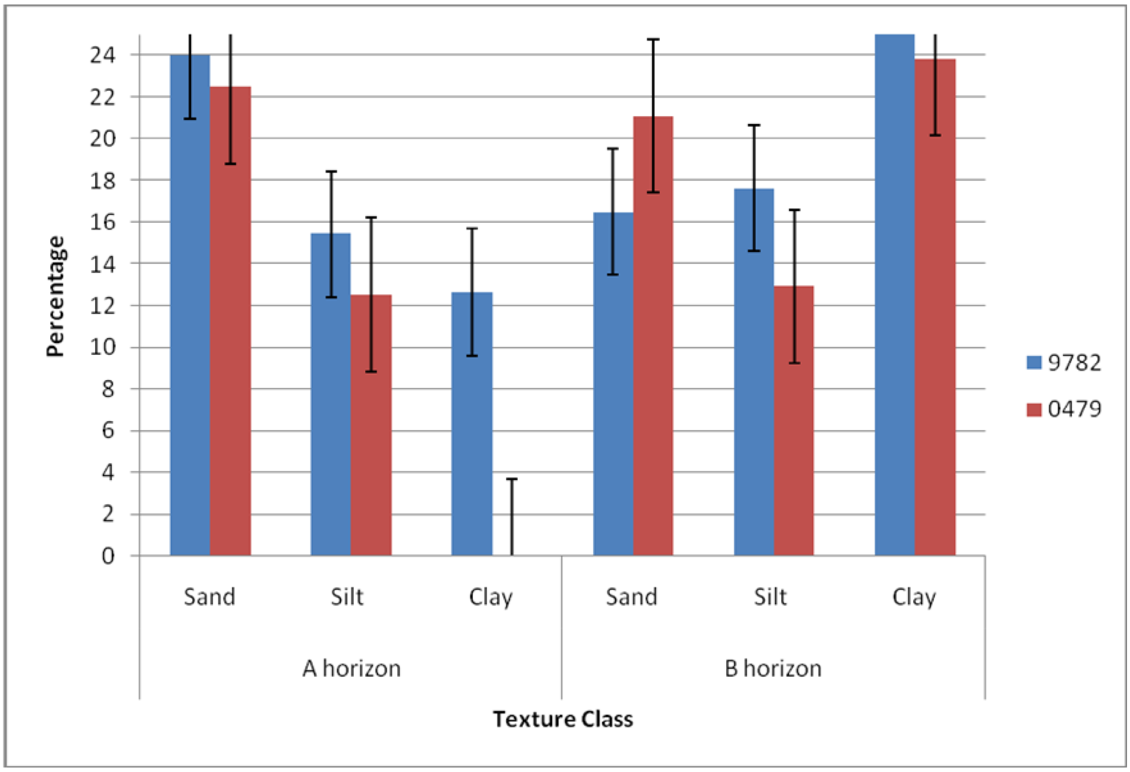
Appendix 5.7. Means of the percent organic carbon for the various site classes



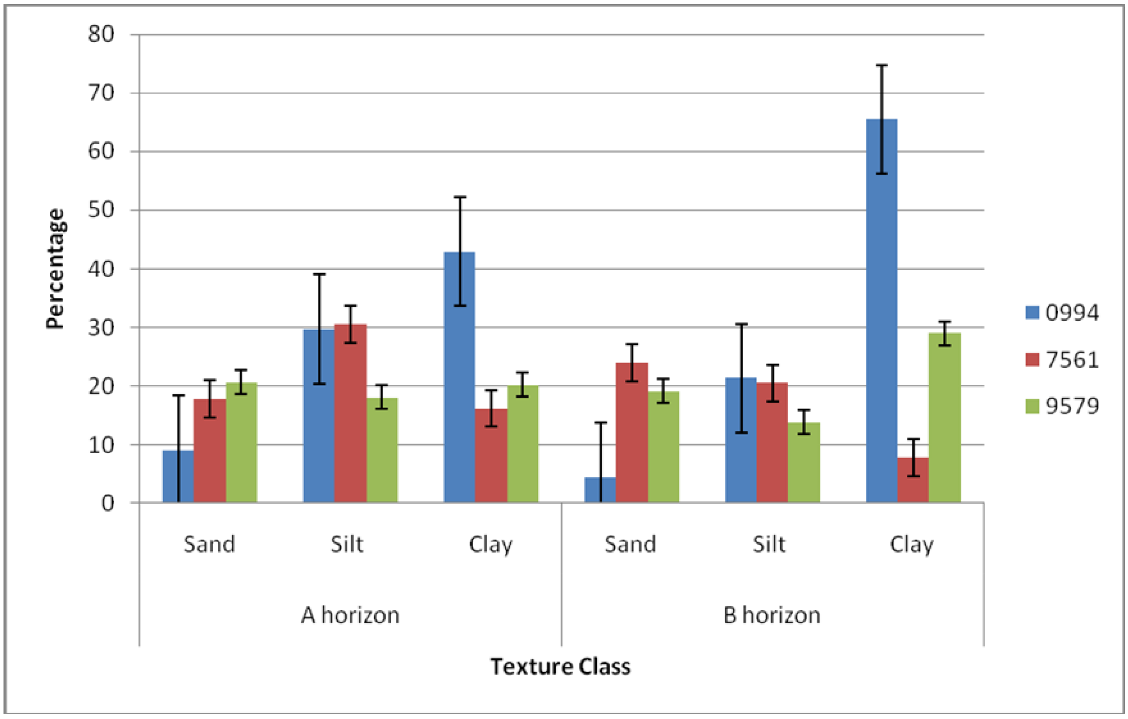
Appendix 5.8. Means of AMBIC phosphorus for the various vegetation change site classes.



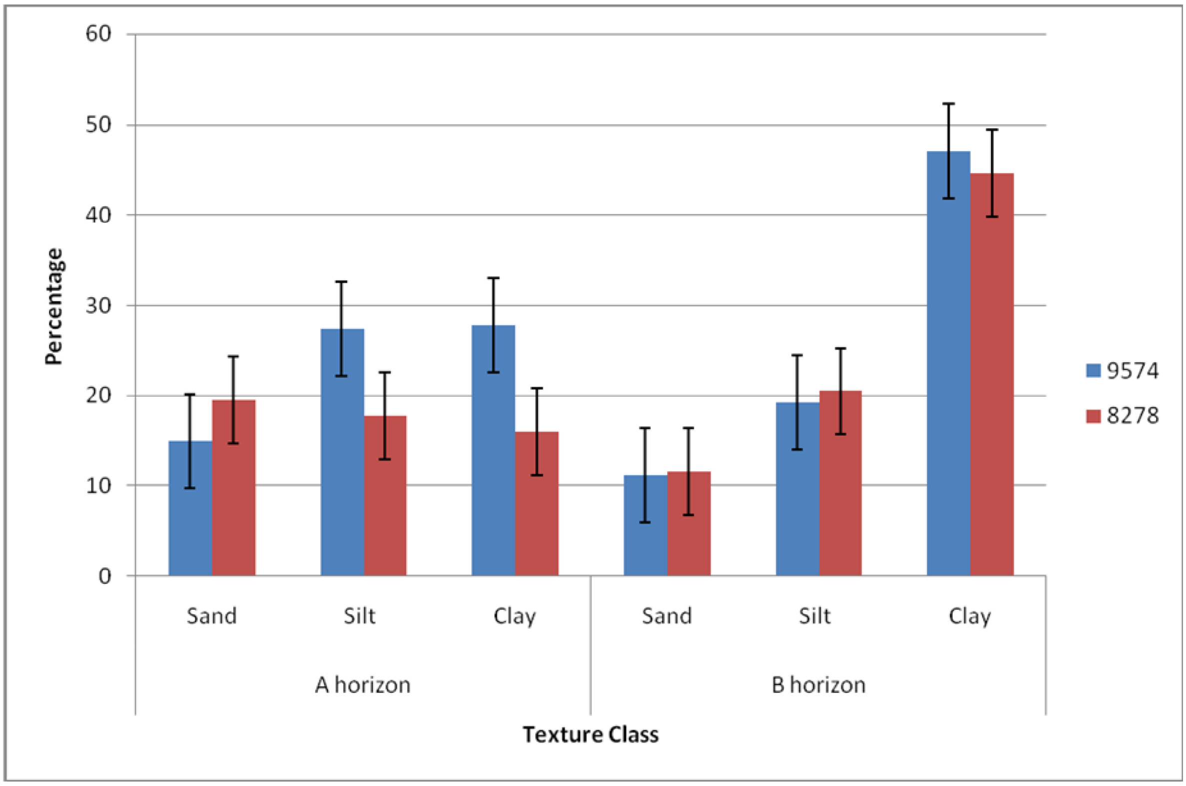
Appendix 5.9. Means of the texture class percentages of the ‘no-change’ classes



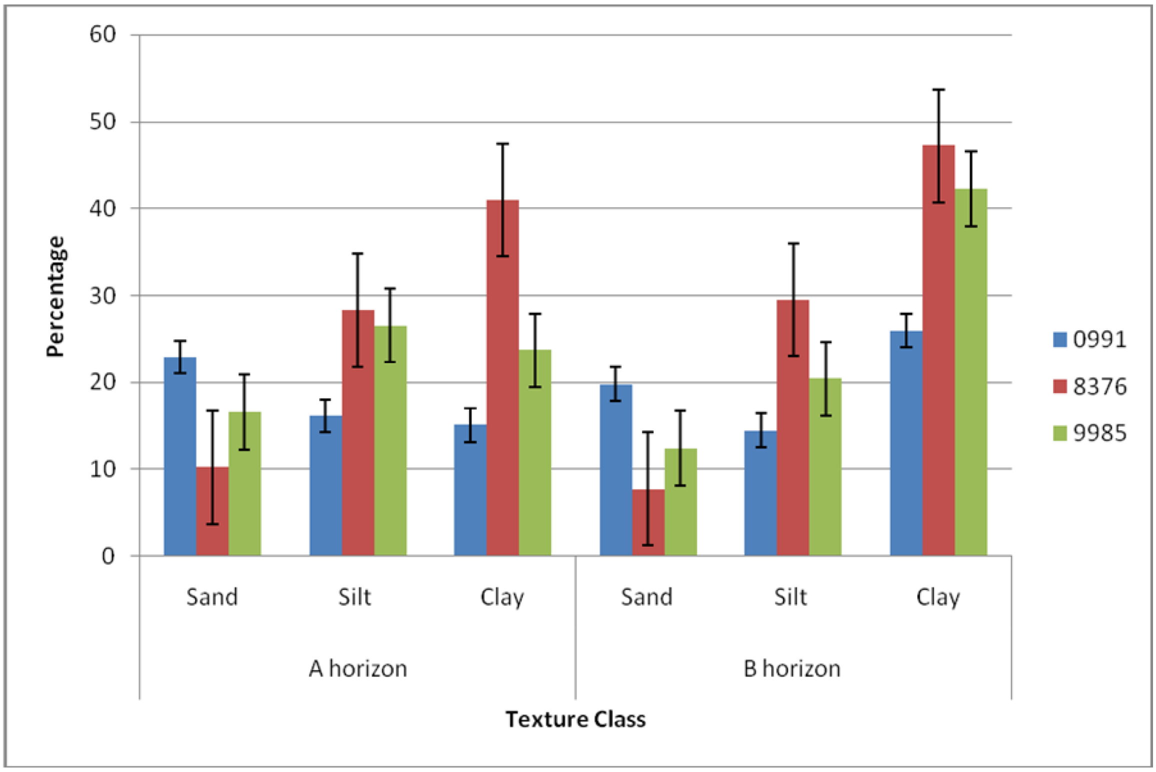
Appendix 5.10. Means of the texture class percentages of the ‘slight increase’ classes



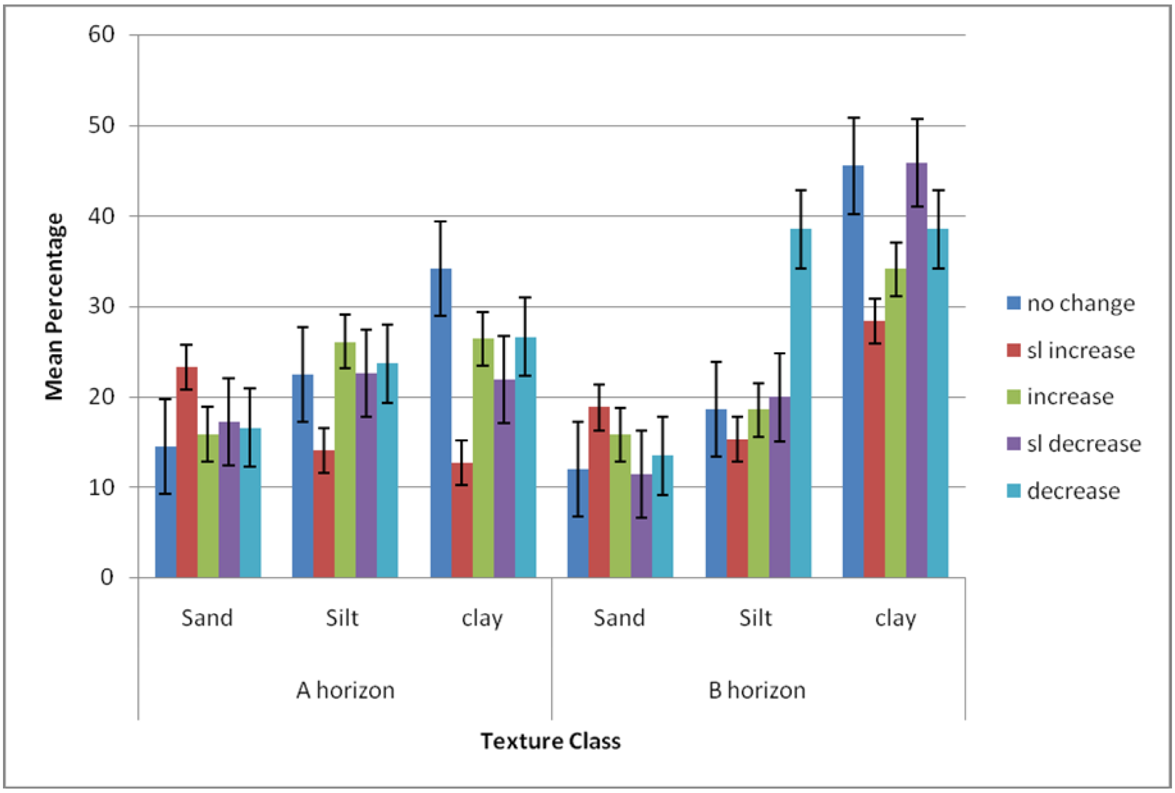
Appendix 5.11. Means of the texture class percentages of the 'increase' classes



Appendix 5.12. Means of the texture class percentage of the 'slight decrease' classes



Appendix 5.13. Means of the texture class percentage of the 'decrease' classes



Appendix 5.14. Averages of the percentage of the texture class for the different sites.

Appendix 6. pH and exchangeable acidity for the various sites

Appendix 6.1. pH and exchangeable acidity for the ‘no-change’ sites

Site number	% change	Soil form and family	Topsoil			Subsoil		
			pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)	pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)
0894	4	Oa 1210	6.26	7.28	0.020	6.17	7.45	0.030
0894	4	Gs 1111	5.67	6.96	0.008	4.93	6.93	0.264
0894	4	Oa 1210	5.02	6.53	0.000	5.19	6.84	0.000
0894	4	Gs 1111	5.18	6.54	0.000	5.13	6.12	0.002
0898	2	Hu 2200	5.10	6.24	0.008	4.74	6.24	0.116
0898	2	Hu 2200	4.77	5.96	0.022	4.68	6.03	0.076
0898	2	Sw 1111	4.86	6.15	0.010	4.68	6.11	0.110
0898	2	Hu 2200	4.89	5.89	0.000	4.33	5.86	0.562
0898	2	Sw 1111	5.38	5.94	0.322	4.63	5.90	0.048
0898	2	Cv 3200	5.25	5.95	0.006	4.94	6.06	0.010
9570	5	Ms 1100	5.71	6.62	0.002	hard rock		
9570	5	Ms 1100	5.73	6.23	0.000	hard rock		
9570	5	Oa 1120	5.77	6.60	0.000	5.76	6.69	0.000
9570	5	Se 1110	5.78	6.58	0.000	5.79	6.54	0.000
8168	3	Sw 1111	6.19	7.54	0.002	5.94	7.56	0.036
8168	3	Ms 1100	5.86	7.03	0.000	hard rock		
8168	3	Ms 1100	5.96	7.10	0.000	hard rock		
8168	3	Sw 1111	5.95	7.13	0.000	6.01	7.25	0.000

Appendix 6.2. pH and exchangeable acidity for the ‘slight increase’ sites

Site number	% change	Soil form and family	A horizon			B horizon		
			pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)	pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)
9782	10	Gs 1111	5.34	6.22	0.000	5.36	6.23	0.000
9782	10	Ms 2100	5.43	6.65	0.010	hard rock		
9782	10	Ms 2100	4.96	6.28	0.056	hard rock		
9782	10	Gs 1111	4.95	6.51	0.000	4.64	5.94	0.084
0479	13	Vf 1110	5.32	6.35	0.002	5.29	6.67	0.014
0479	13	Fw 2110	5.32	6.33	0.000	5.35	6.68	0.000
0479	13	Gs 1111	5.30	6.40	0.000	5.31	6.41	0.000
0479	13	Gs 1111	5.34	6.33	0.000	5.41	6.51	0.000

Appendix 6.3. pH and exchangeable acidity for the ‘increase’ sites

Site number	% change	Soil form and family	A horizon			B horizon		
			pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)	pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)
0994	35	Sw 1111	5.85	6.97	0.000	4.65	5.95	0.400
0994	35	Hu 3100	4.73	6.02	0.200	5.31	6.32	0.004
0994	35	Sw 1111	5.26	6.12	0.000	4.61	6.27	0.926
0994	35	Ms 1100	4.94	5.81	0.000	hard rock		
0994	35	Oa 1110	5.16	5.82	0.000	5.29	6.17	0.574
9579	47	Bo 1110	5.03	6.06	0.000	5.14	6.28	0.000
9579	47	Bo 1110	5.20	6.20	0.000	5.25	6.31	0.000
9579	47	Va 1211	5.04	6.16	0.000	5.56	6.25	0.130
9579	47	Ms 1100	4.73	5.93	0.000	4.86	6.15	0.000
7561	30	Gs 1111	5.31	6.27	0.000	5.34	6.29	0.000
7561	30	Ms 1100	5.45	6.36	0.000	hard rock		
7561	30	Gs 1111	5.57	6.45	0.000	5.69	6.4	0.000
7561	30	Ms 1100	5.71	6.51	0.000	hard rock		

Appendix 6.4. pH and exchangeable acidity for the ‘slight decrease’ sites

Site number	% change	Soil form and family	A horizon			B horizon		
			pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)	pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)
9574	-9	Bo 1110	5.47	6.3	0.000	5.56	6.20	0.000
9574	-9	Ms 1100	5.59	6.31	0.000	hard rock		
9574	-9	Ms 2100	5.63	6.53	0.000	hard rock		
9574	-9	Gs 2121	5.23	6.49	0.000	5.33	6.50	0.000
8278	-12	Sn 1000	6.58	7.23	0.000	6.62	7.62	0.000
8278	-12	Oa 2120	6.48	7.42	0.000	6.35	7.49	0.000
8278	-12	Hu 3200	6.47	7.38	0.000	6.23	7.28	0.000
8278	-12	Hu 3200	6.33	7.43	0.000	6.15	7.21	0.000

Appendix 6.5. pH and exchangeable acidity for the ‘decrease’ sites

Site number	% change	Soil form and family	A horizon			B horizon		
			pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)	pH KCl	pH H_2O	Exchangeable acidity ($cmol_c$/kg soil)
0991	-40	Oa 1110	4.98	6.32	0.000	5.42	6.51	0.000
0991	-40	Va 2111	5.37	6.35	0.000	5.51	6.39	0.020
0991	-40	Oa 1110	5.54	6.53	0.000	4.71	5.83	0.070
0991	-40	Oa 1110	5.06	5.92	0.000	5.26	6.13	0.000
9985	-42	Sw 1111	4.98	6.07	0.000	5.14	6.41	0.004
9985	-42	Sw 1121	4.97	6.06	0.012	5.18	6.56	0.000
9985	-42	Oa 1110	5.07	6.29	0.000	5.75	6.72	0.000
9985	-42	Oa 1110	5.16	6.29	0.000	5.74	6.8	0.000
8376	-65	Gs 1112	6.76	7.14	0.000	6.38	7.28	0.000
8376	-65	Va 1111	5.98	6.78	0.000	5.87	6.57	0.000
8376	-65	Sw 1111	5.94	6.85	0.000	6.12	7.21	0.000

Appendix 7. Exchangeable bases, organic carbon and phosphorus for the various sites

Appendix 7.1. Exchangeable bases, organic carbon and phosphorus for the 'no-change' sites

		Topsoil							Subsoil						
Site name	**Soil form + family**	**Ca ($cmol^+$/ Kg)**	**Mg ($cmol^+$/ Kg)**	**Na ($cmol^+$/ Kg)**	**K ($cmol^+$/ Kg)**	**Total ($cmol^+$/Kg)**	**O C %**	**P (mg/kg)**	**Ca ($cmol^+$/Kg)**	**Mg ($cmol^+$/Kg)**	**Na ($cmol^+$/Kg)**	**K ($cmol^+$/Kg)**	**Total ($cmol^+$/Kg)**	**O C %**	**P (mg/kg)**
0894	Oa 1210	6.14	4.04	0.87	1.36	12.40	4.21	7.05	2.91	2.86	1.19	0.44	7.40	1.11	5.68
0894	Gs 1111	3.40	2.05	0.75	1.63	7.84	2.61	10.00	1.33	1.42	0.63	0.90	4.28	1.28	5.48
0894	Oa 1210	6.86	3.18	0.65	1.20	11.89	3.99	7.84	3.37	2.62	0.71	0.50	7.20	1.05	4.89
0894	Gs 1111	6.43	3.30	0.63	1.16	11.51	3.94	7.84	3.44	2.86	0.55	0.55	7.39	1.87	7.64
0898	Hu 2200	4.36	3.25	0.70	1.82	10.12	3.93	5.87	3.00	1.77	0.57	0.65	5.98	2.75	3.91
0898	Hu 2200	4.57	2.79	0.61	2.04	10.01	4.62	10.79	2.74	2.42	0.57	0.64	6.38	3.33	4.30
0898	Sw 1111	9.79	4.40	0.69	1.11	15.98	5.59	7.45	3.62	2.65	0.65	0.57	7.50	3.53	6.46
0898	Hu 2200	12.76	5.53	0.84	0.88	20.00	5.78	10.00	2.59	2.24	0.50	0.49	5.83	3.54	8.23
0898	Sw 1111	15.75	5.18	0.59	1.48	22.99	5.96	1.32	6.19	3.49	0.62	0.81	11.11	4.27	0.46
0898	Cv 3200	11.54	6.82	0.85	1.69	20.89	7.23	3.76	8.81	5.73	0.79	0.72	16.04	4.48	1.45
9570	Ms 1100	9.69	7.83	1.87	0.14	19.54	2.00	4.70	11.31	9.65	2.88	0.13	23.97	0.76	4.70
9570	Ms 1100	10.01	8.67	0.10	0.43	19.22	3.12	4.89	2.57	12.07	0.31	0.11	15.06	1.60	4.89
9570	Oa 1120	9.32	6.08	0.06	0.49	16.15	2.60	0.19	10.86	5.86	0.76	0.18	17.66	1.87	below detection
9570	Se 1110	12.00	5.80	0.70	2.01	20.51	3.81	53.63	hard rock						
8168	Sw 1111	2.60	1.16	0.42	0.42	4.60	0.85	9.22	2.84	2.22	0.63	0.22	5.91	0.96	6.27
8168	Ms 1100	8.02	3.11	0.46	1.01	12.60	2.06	11.57	hard rock						
8168	Ms 1100	9.20	1.80	0.46	0.44	11.90	2.33	9.41	hard rock						
8168	Sw 1111	4.62	1.92	0.47	0.79	7.79	1.78	2.65	4.98	3.14	0.59	0.81	9.52	0.83	1.32

Appendix 7.2. Exchangeable bases, organic carbon and phosphorus for the 'slight increase' in tree density sites

		Top horizon							Sub horizon						
Site name	**Soil form + family**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**
9782	Gs 1111	12.78	8.07	0.98	1.15	22.98	4.14	4.30	22.65	0.64	0.38	0.17	23.85	1.75	3.52
9782	Ms 2100	1.47	1.18	0.77	0.23	3.65	0.91	6.66	hard rock						
9782	Ms 2100	1.79	1.33	0.87	0.36	4.35	1.10	6.86	hard rock						
9782	Gs 1111	0.97	0.85	0.64	0.43	2.89	0.82	10.79	0.87	2.68	0.71	0.25	4.52	0.44	5.09
0479	Vf 1110	3.16	1.15	0.57	0.51	5.39	1.03	9.41	3.65	1.70	0.72	0.14	6.21	0.49	4.70
0479	Fw 2110	2.64	1.27	0.54	1.01	5.46	1.57	10.00	3.64	1.46	0.64	0.13	5.87	0.72	8.23
0479	Gs 1111	3.22	2.28	0.68	0.55	6.73	1.41	9.41	2.34	2.38	0.67	0.23	5.62	1.11	6.86
0479	Gs 1111	3.26	2.25	0.70	0.75	6.95	1.46	8.04	2.95	2.85	0.58	0.16	6.54	0.97	5.87

Appendix 7.3. Exchangeable bases, organic carbon and phosphorus for the 'increase' in tree density sites

		Top horizon							Sub horizon						
Site name	**Soil form + family**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**
0994	Sw 1111	9.18	5.79	0.81	1.09	16.87	5.31	17.67	3.18	2.23	0.68	0.40	6.48	2.77	8.82
0994	Hu 3100	2.82	2.64	0.39	0.17	6.02	3.74	9.41	1.91	2.15	0.45	0.07	4.58	0.76	7.05
0994	Sw 1111	12.88	3.86	0.43	0.48	17.65	4.72	4.73	2.02	2.52	0.65	0.08	5.27	0.91	0.95
0994	Ms 1100	9.82	3.88	0.61	0.85	15.16	4.47	11.41	hard rock						
0994	Oa 1110	16.28	5.95	0.57	0.43	23.23	4.63	10.02	5.71	4.47	0.64	0.07	10.89	2.80	1.51
9579	Bo 1110	4.26	3.21	0.75	0.53	8.76	2.75	17.27	3.48	3.48	0.66	0.15	7.77	1.81	7.84

Appendix 7.3. (continued)

		Topsoil							Subsoil						
Site name	**Soil form + family**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**
9579	Bo 1110	4.64	3.89	1.02	0.99	10.54	3.57	16.09	5.94	7.05	1.36	0.08	14.42	1.89	6.27
9579	Va 1211	1.38	1.47	0.08	0.40	3.18	1.38	60.31	1.56	1.63	0.76	0.33	4.28	0.98	8.82
9579	Ms 1100	2.48	2.97	0.56	0.25	6.26	2.58	7.64	3.59	4.85	0.35	0.05	8.89	1.96	9.61
7561	Gs 1111	9.93	9.17	0.26	0.24	19.61	3.53	6.07	11.74	1.69	0.14	0.39	13.97	2.60	3.91
7561	Ms 1100	7.32	5.43	0.08	0.13	12.95	2.82	4.30	hard rock						
7561	Gs 1111	10.40	4.48	0.06	0.10	15.04	1.06	0.00	16.07	3.07	0.41	0.07	19.63	0.41	below detection
7561	Ms 1100	10.01	8.67	0.10	0.43	19.22	4.41	4.11	hard rock						

Appendix 7.4. Exchangeable bases, organic carbon and phosphorus for the ‘slight decrease’ in tree density sites

	Top horizon								**Sub horizon**						
Site name	**Soil form + family**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**	**Ca (cmol$^+$/Kg)**	**Mg (cmol$^+$/Kg)**	**Na (cmol$^+$/Kg)**	**K (cmol$^+$/Kg)**	**Total (cmol$^+$/Kg)**	**O C %**	**P (mg/kg)**
9574	Bo 1110	14.06	4.84	0.57	1.11	20.58	3.83	4.50	14.81	6.14	0.77	0.59	22.31	3.17	4.70
9574	Ms 1100	6.53	3.51	0.58	1.24	11.87	2.66	9.22	hard rock						
9574	Ms 2100	5.33	4.09	0.51	1.04	10.97	3.00	7.25	hard rock						
9574	Gs 2121	13.99	5.85	0.64	0.62	21.10	4.74	6.86	no sub horizon						
8278	Sn 1000	8.76	6.85	4.19	0.21	20.01	1.31	10.00	5.31	8.48	10.20	0.06	24.03	0.16	4.30
8278	Oa 2120	8.79	4.33	0.81	0.16	14.10	1.53	9.22	5.57	2.42	0.69	0.30	8.98	0.77	14.13

Appendix 7.4. (continued)

		Top horizon							Sub horizon						
Site name	Soil form + family	Ca (cmol+/Kg)	Mg (cmol+/Kg)	Na (cmol+/Kg)	K (cmol+/Kg)	Total (cmol+/Kg)	O C %	P (mg/kg)	Ca (cmol+/Kg)	Mg (cmol+/Kg)	Na (cmol+/Kg)	K (cmol+/Kg)	Total (cmol+/Kg)	O C %	P (mg/kg)
8278	Hu 3200	4.48	2.28	0.69	2.08	9.53	1.95	19.63	4.79	6.67	2.17	0.04	13.67	1.27	7.05
8278	Hu 3200	3.42	3.34	0.68	0.14	7.58	1.18	9.41	7.30	8.77	1.49	0.18	17.73	2.74	8.23

Appendix 7.5. Exchangeable bases, organic carbon and phosphorus for the ‘decrease’ in tree density sites

		Top horizon							Sub horizon						
Site name	Soil form + family	Ca (cmol+/Kg)	Mg (cmol+/Kg)	Na (cmol+/Kg)	K (cmol+/Kg)	Total (cmol+/Kg)	O C %	P (mg/kg)	Ca (cmol+/Kg)	Mg (cmol+/Kg)	Na (cmol+/Kg)	K (cmol+/Kg)	Total (cmol+/Kg)	O C %	P (mg/kg)
0991	Oa 1110	2.29	1.02	0.64	0.10	4.05	0.85	14.91	2.85	3.33	4.68	0.06	10.93	0.77	4.11
0991	Va 2111	5.75	3.93	1.11	1.31	12.09	2.71	27.10	4.79	6.67	2.17	0.04	13.67	1.27	7.05
0991	Oa 1110	4.75	1.68	0.48	0.12	7.02	2.17	16.88	2.77	1.78	0.87	0.16	5.58	1.09	13.74
0991	Oa 1110	5.08	2.53	0.57	0.15	8.31	2.03	8.51	7.64	2.30	0.49	0.15	10.57	2.84	11.34
9985	Sw 1111	5.80	5.60	0.53	1.64	13.57	3.05	7.64	3.18	2.23	0.68	0.40	6.48	2.77	8.82
9985	Sw 1121	3.94	5.18	0.71	0.48	10.31	3.34	11.38	2.02	2.52	0.65	0.08	5.27	0.91	0.95
9985	Oa 1110	9.09	8.43	0.71	1.10	19.33	3.59	5.48	7.67	9.28	0.91	0.46	18.32	2.55	2.53
9985	Oa 1110	7.97	6.52	0.64	0.74	15.88	3.75	12.56	7.30	8.77	1.49	0.18	17.73	2.74	8.23
8376	Gs 1112	20.22	10.42	1.39	0.30	32.33	2.05	4.70	15.76	13.12	5.84	0.08	34.79	0.70	3.12
8376	Va 1111	25.31	11.47	1.47	0.63	38.89	1.91	3.78	22.46	9.6	2.33	0.31	34.7	1.81	3.21
8376	Sw 1111	20.26	11.14	2.55	0.40	34.34	1.95	5.09	19.34	9.7	6.56	0.22	35.82	1.48	2.93

Appendix 8. Particle size distribution tables for the various sites

Appendix 8.1. Texture classes for the 'no-change' sites

		A horizon					B horizon				
Site number	Soil form and family	Coarse Sand	Medium Sand	Fine Sand	Silt	Clay	Coarse Sand	Medium Sand	Fine Sand	Silt	Clay
		%					%				
0894	Oa 1210	7.61	6.46	11.78	23.73	50.42	6.03	4.16	10.76	17.20	61.86
0894	Gs 1111	2.56	14.41	35.11	16.84	31.07	3.55	10.96	25.31	15.37	44.82
0894	Oa 1210	2.43	12.26	26.69	22.99	35.63	1.04	4.25	15.93	11.75	67.03
0894	Gs 1111	7.83	14.05	24.99	20.29	32.83	4.34	8.37	26.97	18.19	42.14
0898	Hu 2200	5.37	3.33	7.29	33.61	50.40	9.95	3.58	5.80	23.44	57.24
0898	Hu 2200	21.40	5.34	5.55	25.30	42.42	17.43	4.12	4.85	19.67	53.92
0898	Sw 1111	11.42	8.01	9.38	27.68	43.51	7.90	5.91	7.32	24.31	54.57
0898	Hu 2200	21.69	5.81	6.23	26.43	39.84	10.57	4.97	5.81	22.45	56.20
0898	Sw 1111	11.63	7.56	9.20	27.18	44.44	6.04	4.57	6.93	29.51	52.95
0898	Cv 3200	19.43	29.68	26.37	13.28	11.24	7.59	6.17	8.59	35.20	42.45
9570	Ms 1100	4.34	4.34	13.12	19.99	58.22	hard rock				
9570	Ms 1100	5.03	7.38	18.83	25.93	42.82	hard rock				
9570	Oa 1120	6.73	8.53	18.92	22.57	43.24	3.63	5.20	14.08	19.73	57.35
9570	Se 1110	6.39	5.91	20.80	34.02	32.89	10.53	7.63	14.88	19.91	47.07
8168	Sw 1111	15.68	24.74	37.08	12.25	10.25	17.81	20.05	28.47	11.97	21.71
8168	Ms 1100	13.73	17.04	27.72	21.10	20.40	hard rock				
8168	Ms 1100	12.14	19.72	27.92	20.76	19.46	hard rock				
8168	Sw 1111	16.29	20.01	33.45	16.32	13.93	16.24	18.85	26.54	14.23	24.14

Appendix 8.2. Texture classes for the 'slight increase' sites

		A horizon					B horizon				
Site number	Soil form and family	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %
		%					%				
9782	Gs 1111	10.9	15.2	21.2	25.4	27.3	9.2	10.6	14.4	22.1	43.6
9782	Ms 2100	24.2	27.7	30.3	11.2	6.7	hard rock				
9782	Ms 2100	9.6	20.5	46.2	13.2	10.5	hard rock				
9782	Gs 1111	14.4	28.6	39.2	11.9	6.1	18.3	19.5	26.7	13.0	22.2
0479	Vf 1110	6.3	12.1	56.9	12.2	12.5	6.2	11.9	51.0	13.0	17.7
0479	Fw 2110	2.3	10.4	59.7	13.5	14.1	2.3	9.9	59.7	12.8	15.1
0479	Gs 1111	2.8	8.0	53.1	12.9	23.1	4.8	6.8	45.5	11.7	31.0
0479	Gs 1111	2.1	4.8	51.2	11.6	30.3	4.0	4.2	46.2	14.0	31.4

Appendix 8.3. Texture classes for the 'increase' sites

		A horizon					B horizon				
Site number	Soil form and family	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %
		%					%				
0994	Sw 1111	7.7	6.1	8.7	32.4	45.1	3.9	2.8	6.4	20.1	66.8
0994	Hu 3100	4.8	3.8	6.4	24.6	60.8	0.8	1.0	5.3	19.2	73.7
0994	Sw 1111	6.5	10.2	21.8	27.0	34.3	0.9	1.5	9.8	25.3	62.2
0994	Ms 1100	8.1	7.3	18.2	28.7	37.5	hard rock				
0994	Oa 1110	4.6	5.7	16.6	36.3	36.7	6.3	4.1	10.2	20.1	59.1
9579	Bo 1110	9.3	18.1	30.7	19.0	22.6	9.5	18.9	29.2	15.1	27.0
9579	Bo 1110	8.2	10.7	37.2	21.6	22.1	8.7	9.7	32.0	13.6	35.8
9579	Va 1211	19.4	28.3	25.5	11.9	14.6	12.9	22.4	27.9	12.7	23.9
9579	Ms 1100	11.9	18.0	29.5	19.3	21.0	hard rock				

Appendix 8.3. (continued)

		A horizon					B horizon				
Site number	Soil form and family	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %
		%					%				
7561	Gs 1111	9.9	10.5	29.3	35.0	15.0	15.0	12.1	27.4	31.0	14.3
7561	Ms 1100	13.3	10.9	25.1	32.2	18.3	hard rock				
7561	Gs 1111	39.9	16.1	20.5	18.8	4.4	61.5	14.5	12.7	9.8	1.3
7561	Ms 1100	6.5	8.3	22.7	35.7	26.6	hard rock				

Appendix 8.4. Texture classes for the ‘slight decrease’ sites

		A horizon					B horizon				
Site number	Soil form and family	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %
		%					%				
9574	Bo 1110	27.0	10.9	15.7	19.6	27.0	17.6	10.4	19.1	19.9	32.8
9574	Ms 1100	13.6	8.7	24.9	24.5	28.3	hard rock				
9574	Ms 2100	9.1	8.9	25.5	28.8	27.7	hard rock				
9574	Gs 2121	12.5	7.1	15.5	36.9	28.0	3.2	3.8	13.3	18.6	61.1
8278	Sn 1000	5.5	10.6	41.6	14.5	28.1	3.7	7.6	34.3	19.6	34.5
8278	Oa 2120	6.9	13.2	40.6	13.0	26.6	9.1	9.7	32.9	18.6	29.4
8278	Hu 3200	6.6	9.6	42.7	25.0	16.3	7.4	5.6	4.9	23.6	58.3
8278	Hu 3200	3.7	7.7	46.5	18.4	23.9	14.8	5.0	3.7	20.1	56.2

Appendix 8.5. Texture classes for the 'decrease' sites

		A horizon					B horizon				
Site number	Soil form and family	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %	Coarse Sand %	Medium Sand %	Fine Sand %	Silt %	Clay %
		%					%				
0991	Oa 1110	8.6	23.2	47.5	11.6	8.9	9.9	18.9	32.8	9.9	28.8
0991	Va 2111	7.8	17.3	36.8	18.5	19.2	8.9	12.4	25.3	14.1	39.7
0991	Oa 1110	6.2	21.7	40.4	18.1	13.3	6.5	19.9	37.7	14.9	21.3
0991	Oa 1110	5.5	20.6	38.5	16.3	18.8	7.0	22.2	37.7	19.2	14.2
9985	Sw 1111	15.2	10.9	25.3	27.1	21.3	8.6	7.6	17.4	26.1	40.5
9985	Sw 1121	12.5	11.9	35.7	24.3	15.3	8.8	9.9	20.8	23.3	37.5
9985	Oa 1110	13.3	9.2	20.6	27.5	29.1	1.8	3.8	12.7	17.4	64.6
9985	Oa 1110	7.8	10.6	25.9	26.9	28.9	13.7	18.0	27.8	14.7	26.3
8376	Gs 1112	11.1	7.5	13.3	27.2	40.6	12.4	3.7	5.7	29.9	48.0
8376	Va 1111	7.1	7.6	15.7	30.3	39.1	7.9	6.9	14.3	31.0	40.1
8376	Sw 1111	6.8	7.2	15.5	27.5	43.1	4.6	4.9	9.6	27.4	53.4