Impact of afforestation-induced grassland fragmentation on soil and microclimate in Groenvaly, South Africa

by

Sarah Charlotte Butler

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MSc: Geography

In the Faculty of Natural and Agricultural Sciences

Department of Geography, Geoinformatics and Meteorology

University of Pretoria

Pretoria

Supervisors:

Prof. P.D. Sumner

Prof. J.W.H. Ferguson*

*Centre for Environmental Studies, University of Pretoria

I, Sarah Charlotte Butler, declare that this dissertation, which I hereby submit for the degree MSc: Geography at the University of Pretoria, is my own work and has not previously been submitted by me at this or any other tertiary institution.

SIGNATURE:………………………………

DATE:……………………………………........

ABSTRACT

Afforestation is considered to be one of the leading land-use changes affecting ecosystem function and diversity. This study investigates the impact of pine afforestation on microclimate and soil in fragments of highly vulnerable Afromontane grassland at Groenvaly. Three major challenges for afforestation research are identified as (i) the range and intricacy of the impact of afforestation, (ii) differences in measurement and monitoring periods and (iii) a lack of focus on biomes adjacent to plantations. The approach here aimed to address these three areas. Air microclimate data were collected for 24 months within a plantation site, a control grassland site and a grassland fragment using three Davis Vantage Pro2 weather stations. Soil temperature data were logged on iButtons^{TM} for 18 months and soil samples from four seasons were analysed for moisture content, nitrogen (N), nitrate, ammonium, phosphorous (P), pH, sodium (Na), calcium (Ca), potassium (K), magnesium (Mg) and soil organic carbon (SOC). All data were statistically analysed at within-site, between-site, seasonal and mean scales and each analysis highlighted different conclusions. Results for the chemicals properties of the individual grassland fragments did not exhibit within-site variation except for K and P and between-site variation was only evident for N, nitrate, moisture and SOC. Solar irradiance was reduced in the fragments only during winter while SOC and P in the fragments only differed from the control grassland sites in summer and autumn respectively. Mean values for P, pH, Na, Ca, K, SOC and soil moisture within the fragments' soil were between those of the control grassland and the plantation while N and Mg values were closer to the plantation than the control grassland. Mean values for air temperature, wind speed, solar irradiance and humidity within the fragment were closer to the control grassland than the plantation. Soil temperatures at 2cm in the fragments were similar to the control grassland, while temperatures at 10cm below the surface were lower than both the control grassland and the plantation sites in winter. Maximum air temperatures in the fragments were lowered in summer and raised in winter but minimum air temperatures were raised in the fragments across all seasons. Results of this study show that there are different impacts in different seasons while overall mean data indicate that the fragments' soil is affected, and microclimate is unaffected, by the plantation. The impact of the change in soil

and microclimate in grassland fragments requires more investigation to determine if grassland fragments are a suitable conservation strategy in pine plantations.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIX LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Globally, land-use change is a topic that has attracted much interest due to its potential impacts on long-term sustainability (Chen *et al*., 2008). Commercial plantations, which are a major form of land-use change, have a proven impact on a variety of natural cycles (Farley, 2007) ranging from hydrological, to micro-climatic to carbon storage. While many factors may affect ecosystem functioning and diversity, afforestation and deforestation are considered to be a leading cause (Macdonald *et al.*, 2009). Although the global total area under plantation decreased by 0.18% over the years 2000 – 2005, the production and consumption of key wood products and wood energy are expected to rise to the year 2030 (FAO, 2009). Growth in this industry will mainly be driven by European renewable energy policies, an increased demand for environmental services, institutional changes allowing enhanced market access for the private sector and improvements in forest science and technology (FAO, 2009). As the forestry industry grows, so too will the demand for knowledge on the extent of the industry's impact. The necessity to understand the impacts of afforestation on the physical and biological properties of soil, and its chemical constituents, will thus continue to be an essential driver of afforestation research into the future.

1.1 Afforestation research

Afforestation research evolved from studies on fragmentation. Fragmentation occurs both naturally and as a result of human activities. Initially, the focus of fragmentation research was on localised land use change events but research subsequently expanded into the study of the impacts on fauna and flora. Fragmentation, and its driving forces, has been a topic of research since the early 1960s when MacArthur and Wilson's (1963) equilibrium theory of island biogeography was much debated (Saunders *et al.*, 1991). Indeed, fragmentation of habitats has been cited as a leading cause of species extinction (Diamond, 1984; 1989). The aims of fragmentation research are invariably aligned with determining what, if any, impact there is on the living environment and the implications thereof. Thus, in areas where pine forests are indigenous, the focus has been on conservation and protection of forests with the major threats being urbanisation and agricultural pastureland. The opposite is true in regions where the *Pinus* genus is not indigenous. *Pinus* plantations in these regions remain mono-cultural in nature, lack the composition and structure of true forests and, thus are considered to have a negative impact on biodiversity due to the total transformation of the natural ecosystem (Everard *et al.*, 1994). Afforestation research therefore traditionally had one of two aims; to assess either (i) the impacts on indigenous forests and plantations as a result of adjacent land use changes, or (ii) the impacts on indigenous biomes as a result of commercial afforestation.

Because afforestation can have a broad impact, research has historically focussed on particular topics including the hydrological cycle (*e.g.* Fahey and Jackson, 1997), the nutrient cycle (*e.g.* Farley and Kelly, 2004), soil and air microclimate (*e.g.* Menezes *et al.*, 2002), soil physical and chemical properties (*e.g.* Tate *et al.*, 2007), fauna (*e.g.* Allan *et al.*, 1997) and flora (*e.g.* Bredenkamp *et al.*, 1999). As a result of the interaction of plantation and grassland microclimate occuring at several levels, individual studies tend to focus on one or two specific variables or cycles. While many different studies contribute to a holistic appreciation of the impact of afforestation on surrounding environments, three major challenges remain. The first is the range and intricacy of the impact of afforestation. Due to its global presence, commercial afforestation can, and does, have an impact on a variety of biomes and cycles in many regions. Impacted biomes include indigenous forests (Denyer *et al.*, 2006), pasturelands (Mendham *et al.*, 2004) and natural grasslands (Chen *et al.*, 2000). The second challenge is a discrepancy in measurement periods between different studies of same variables; this creates difficulties in the comparison and interpretation of sites. Air microclimate datasets range from two days (Gehlhausen *et al.*, 2000) to a more substantial 18 months (Porté *et al.*, 2004) with the most common period being one growing season. On the contrary, relatively few soil sampling methods have involved sampling on more than one occasion. Where soil sampling was more frequent, evidence of variation both within and between seasons was observed (*e.g.* Hart *et al*., 1993; Chen *et al*., 2003; Cao *et al*., 2007). The third is that while research into the impacts of afforestation on surface and soil microclimate is well represented in many regions, the focus has largely been on the changes directly beneath the plantation canopy. Very few studies have investigated the affects of plantations on adjacent biomes. While it may be argued that the most significant impact is noticed directly under the plantation, the impact is not limited to plantation boundaries (see Billings, 2006 and Denyer *et al.*, 2006). Despite these three challenges, some definite microclimatic and soil impacts are clear, such as declines in carbon, nitrogen and pH, but others are less so, such as cation concentrations and organic matter. In all cases, impacts on certain natural cycles are observed and considered to be due to significant changes in microclimate, soil physical properties and nutrient levels. A more in-depth review of afforestation research follows in Chapter 2.

The grassland biome, specifically, is critically endangered (Olsen and Dinerstein, 1998; Reyers *et al.*, 2001) and according to Rebelo (1997) is the southern African biome most in need of conservation. Afforestation, mining and urban development are considered the greatest threat to grasslands based on the perceived impact on grassland structure, function and composition (Neke and du Plessis, 2004). A transformation in land use not only affects the land on which it occurs, it can also be a fragmentation agent and cause separation of the surrounding biome. The vulnerability of the southern African grassland biome to afforestation stems from the climatic and locational requirements for plantations. Undeveloped land with the correct climate, that is unsuitable for other agricultural practices, is ideal for plantations. Typically, land satisfying these criteria is located along the escarpment and in the *lowveld* of southern Africa and both regions contain extensive and diverse grassland. Faunal and floral diversity of grasslands, and its response to fragmentation, has been examined (Rosquist and Prentice, 2000; Schmitt and Seitz, 2002; Adriaens *et al.*, 2006). In particular, Orthoptera, Coleoptera, Mammalia and plant diversity have been studied at Groenvaly with a view to determining viability of grassland fragments within a pine plantation (van Jaarsveld *et al.*, 1998). An investigation into the microclimatic impacts of the Groenvaly plantation is still required as a suitable microclimate is essential for faunal and floral survival. Any change in microclimate conditions within a fragment of grassland may threaten the survival of some species despite other important variables being ideal, such as distance from another fragment and the species' population size.

1.2 The Groenvaly experiment

An experiment, initiated in 1994 by the University of Pretoria, in collaboration with Sappi Forests, was conducted on planned grassland fragmentation within a newly established pine plantation in Groenvaly, South Africa. The aim of the experiment was to foster an understanding of the management and conservation of biodiversity in the highly endemic Afromontane grasslands of the Mpumalanga escarpment (van Jaarsveld *et al.*, 1998). The design of the experiment ensured that grassland fragments were dispersed throughout the experimental and control areas and were similar with regards to climatic variables and physical attributes. Subsequent research at Groenvaly evaluated plant, mammalian and insect taxa pre and post fragmentation and within two years of plantation establishment (see van Jaarsveld *et al.,* 1998, Bredenkamp *et al*., 1999, Johnson *et al*., 2002, Foord *et al.*, 2002 and Foord *et al.*, 2003). The plantation at Groenvaly has since reached maturity and thus provides a suitable base to evaluate the impacts of a pine plantation on the surface and subsurface microclimate of grassland fragments. Commencing in 2008, this study is the first to evaluate the impact of afforestation at Groenvaly on soil and microclimate in grassland fragments.

1.3 Aim and objectives

Afforestation studies have, to date, observed a significant impact of afforestation on soil and microclimate. Future research should look at addressing the three main challenges, namely, dealing with the variety of afforested regions, investigating impacts on adjacent biomes and ensuring sampling method consistency. Groenvaly provides an ideal setting for addressing these challenges, particularly the impact of afforestation on an adjacent biome. Previous research at Groenvaly has investigated the impact of afforestation-induced grassland fragmentation on species richness and species diversity of insects, mammals and vegetation within grassland fragments (see van Jaarsveld *et al.,* 1998, Bredenkamp *et al*., 1999, Johnson *et al*., 2002, Foord *et al*., 2002 and Foord *et al.*, 2003).

The aim of this study is, therefore, to investigate the potential changes in soil properties and microclimate in a 14–year–old pine plantation and in adjacent grassland fragments at an individual, seasonal and a mean scale. The original aim of the Groenvaly habitat fragmentation experiment will be supported by this research which will provide possible underlying reasons for community change and ultimately contribute to conservation and management of afromontane grassland biodiversity. This aim is supported by the following objectives:

1. To compare and evaluate two-year air and soil microclimate (air temperature, solar irradiance, relative humidity, wind speed, soil temperature, soil moisture) data and seasonal soil chemical data from within a pine plantation and within adjacent fragmented grassland in three categories :

    1.1 Individual
    1.2 Seasonal
    1.3 Overall mean

2. If there are significant differences, the possible mechanisms responsible for the observed differences will be evaluated.

1.4 Project outline

The above aim and objectives will be fulfilled over seven chapters. Chapter 1 briefly covers afforestation and its place within the framework of land use change. The Groenvaly project is introduced and followed by the aim and objectives. Chapter 2 discusses afforestation research, themes, methods and the results of published studies, which serve to contextualise the aim and objectives. Chapter 3 provides a detailed description of the Groenvaly study area. Chapter 4 details the methods selected in order to reach the stipulated objectives. Chapter 5 presents the results of the study as well as relevant observations. Chapter 6 discusses the results in Chapter 5 with emphasis on the contrasts of between-site, within-site, seasonal and overall mean results. The consistencies and contradictions with previous work in similar studies are a second focus, the third being an analysis of the possible mechanisms involved. Chapter 7 contains concluding remarks and recommendations pertaining to future research.

CHAPTER 2: LITERATURE RIVIEW[1]

2.1 Development of afforestation research

Afforestation research evolved during the 1940s from studies on habitat fragmentation, where the focus was on localised land use change events which had resulted in fragmentation of indigenous biomes. The aim of fragmentation research was to determine what, if any, impact there is on the living environment and the implications thereof. Studies on the specific impacts of afforestation were thus a logical branch of the fragmentation topic. Initial research on the impact of afforestation was broadly focused on microclimate (Selleck and Schuppert, 1957; Percival *et al.,* 1984b) and soil properties (Percival *et al.,* 1984a). Studies on the impact of afforestation subsequently developed into more detailed investigations on specific microclimatic or soil aspects. Table 2.1 presents a chronological list of microclimatic and soil studies conducted in plantations.

In the 1980s, this field of study progressed to include consideration of the direct impacts of silvicultural afforestation on pastureland. The main goal was to evaluate the impacts of woody vegetation on grazing land and livestock with a view to determining the economically optimum density and species. Research output on this specific type of agroforestry originated mainly from the temperate regions of Europe and South America (see Table 2.1: Fernández *et al*., 2002, Menezes *et al*., 2002, Koukoura and Kyriazopoulos, 2007 and Gea-Izquierdo *et al*., 2009). Few studies investigated the affects that plantations have on adjacent biomes, although there is some evidence that a plantation's impact could extend beyond plantation boundaries (see van Wesenbeeck *et al.,* 2003; Denyer *et al.,* 2006). The subsequent expansion of the research field has been based on country or region-specific factors and has resulted in three focus areas (Table 2.1): impacts on temperate and tropical grassland and tropical forest (southern Africa, South America, Asia), impacts on temperate pastureland (Australasia), silvicultural dynamics and impacts on temperate indigenous forest (Europe).

[1] Altered from the paper prepared for publication under the title: *IMPACT OF COMMERCIAL AFFORESTATION ON MICROCLIMATE AND SOIL: A REVIEW*

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Table 2.1: Published studies on the impact of plantations on soil and microclimate, the location and climate of the studies (where TR = Tropical, TE = Temperate, DSH – Dry Sub-humid, SH = Sub Humid, H = Humid), the age of the stands in years at the time of the studies (where ? = stand age not supplied), the type of study (where 1: air microclimate, 2: soil properties and microclimate, 3: combination of 1 and 2), sampling depths used, monitoring period, number of soil sampling efforts, type of vegetation studied

Reference	**Location & Climate**	**Stand Age (years)**	**Study type**	**Sampling Depths (cm)**	**Monitoring period**	**Sampling effort(s)**	**Vegetation type**
Selleck and Schuppert (1957)	USA, TE	23	1		17 days		Pasture Pine
Percival *et al.* (1984a)	New Zealand, TE	0,3,5,6,7,8,9	2	7.5cm		Seven over seven years	Pine Pasture
Percival *et al.* (1984b)	New Zealand, TE	5,6,7,8,9,10	3	10, 30cm	Once a day for 5 years		Pine Pasture
Yeates (1988)	New Zealand, TE	14	2	0–10, 10–20, 20–30, 30–40cm		Four over nine months	Pine Pasture
Hawke and Wedderburn (1994)	New Zealand, TE	8,9,10,11	1		3 years		Grassland Pine
Parfitt et al. (1997)	New Zealand, TE	20	2	0–10, 10–20cm	Once a month over 7 months		Pasture Pine
Alfredsson *et al.* (1998)	New Zealand, TE	17	2	0–10cm		One	Grassland, Douglas fir Pine
Jaiyeoba (1998)	Nigeria, DSH	2,5,7,10,16,21	2	0–15, 15–30		One	Savanna Pine Eucalypt
Chen *et al.* (2000)	New Zealand, TE	19	2	Bulked: 0–5, 5–10, 10–20, 20–30cm		One	Grassland Pine
Lilienfein *et al.* (2000)	Brazil, TE	20	2	0–15, 15–30, 30–80, 80cm–1.2m, 1.2–2m	6 months	One	Savanna Pine
Turner and Lambert (2000)	Australia, TE	0–25(Pine) 0–35(Euc)	2	0–10cm		One	Pine Eucalypt Pasture
Groenendijk *et al.* (2002)	New Zealand, TE	17,18,19	2	Bulked: 0–6, 6–12, 12–18, 18–24, 24–30cm and from each soil horizon		One	Pasture Pine
Silva-Pando *et al.* (2002)	Spain, TE	?	1		5 months		Grassland Pine
van Wesenbeeck *et al.* (2003)	Columbia, TR	8	2	10–15cm		One	Grassland Pine
Chen *et al.* (2003)	New Zealand, TE	19	2	0–5cm	1 year	Seven	Grassland Pine
Jobbágy and Jackson (2003)	Argentina, TE, H,& SH	11–95	2	20cm		One	Grassland Eucalypt
O'Connell *et al.* (2003)	Australia, TE	6–11	2	0–10, 10–20cm		One	Pasture Eucalypt
Porté *et al.* (2004)	France, TE	38	1		18 months		Grassland Pine
Farley and Kelly (2004)	Ecuador, TE	0–25	2	0–10cm		One	Grassland Pine
Farley *et al.* (2004)	Ecuador, TE	0–25	2	0–10cm		One	Grassland, Pine
Mendham *et al.* (2004)	Australia, TE	30–74	2	0–10cm		One	Pasture Eucalypt
Lima *et al.* (2006)	Brazil, TR	0,4,8,13,29,22, 29,32,33,34	2	0–10, 10–20cm		One	Pasture Eucalypt
Ndala *et al.* (2006)	South Africa, TE	18	2	0–10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, 80–90, 90–100cm and soil core to 25cm		Five over five months	Grassland Pine

Reference	Location & Climate	Stand Age (years)	Study type	Sampling Depths (cm)	Monitoring period	Sampling effort(s)	Vegetation type
Scott *et al.* (2006)	New Zealand, TE	13	2	0–10, 10–20cm	Soil temperature – 13 months	One	Pasture Pine
Tate *et al.* (2007)	New Zealand, TE	7,14	2	0–5cm		One	Pasture Shrubland Pine
Zhao *et al.* (2007)	China, TE	15,22,30	2	0–5, 5–20cm		One	Grassland Pine
Guo *et al.* (2008)	Australia, TE	16	3	0–10, 10–30, 30–60, 60–100cm and >100 cm	3 years (soil temperature); 2 years (soil moisture)	One	Pasture Pine
Hu *et al.* (2008)	China, TE	15,24,30	2	0–10, 10–20, 20–40, 40–60cm		One	Grassland Pine Poplar
Kirschbaum *et al.* (2008)	Australia, TE	15–18	2	0–5, 5–15, 15–30, 30–60, 60–100cm		Two	Pasture Pine
Macdonald *et al.* (2009)	New Zealand, TE	5,8,10,20	2	0–10cm		One	Pasture Pine
Singh *et al.* (2009)	New Zealand, TE	5,8,10,20	2	0–10cm		One	Pasture Pine
Zhao *et al.* (2009)	China, TE	22	2	0–20cm		Four over seven months	Savanna, Grassland Pine
Katsuno *et al.* (2010)	Japan, TE	50	2	6 horizons (up to 2m)		One	Gassland Pine

2.1.1 Grassland and tropical forest focus

Parts of South America’s native subpáramo grassland have been converted into exotic conifer and eucalypt plantations. The results of research on soil acidification and organic carbon (C) in these plantations have shown that afforestation in tropical regions leads to a deep acidic litter layer and higher cation concentrations (Jobbágy and Jackson, 2003; Farley and Kelly, 2004; Lima *et al*., 2006). Aluminium (Al), in particular, was found to increase after afforestation and lead to a secondary increase in acidity (Lilienfein *et al*., 2000). Findings from other studies show that tropical subpáramo grassland biodiversity and species composition decrease in response to afforestation (van Wesenbeeck *et al*., 2003). These conclusions are echoed in studies on montane grassland in South Africa (Allan *et al*., 1997; Johnson *et al*., 2002).

In the dry sub-humid region of Nigeria, Jaiyeoba (1998) observed changes in nutrients based on the age of the pine plantation. Ndala *et al.* (2006) found that soil types have an influence on nutrient differences in temperate Mpumalanga, South Africa. Pine and eucalypt plantations have differing impacts on nutrient levels. Scholes and Scholes (1999), for example, found that the *Pinus patula* plantations lost more nitrogen (N), phosphorous (P), potassium (K), calcium (Ca) and magnesium (Mg) per hectare per year than *Eucalyptus grandis* plantations.

Since the 1950s, afforestation in China has been used as a tool to prevent desertification, stabilise sand dunes (Zhao *et al*., 2007), prevent soil loss, improve soil structure and assist nutrient cycling (Cao *et al*., 2007). Afforestation in Japan is not only a formalised form of agriculture but also occurs naturally through invasion of abandoned grasslands (Katsuno *et al*., 2010). Published studies on afforestation in Asia have been somewhat limited to the last decade. These investigations centred around impacts of afforestation on soil phosphorous P, C and N and, not unexpectedly, some results are region specific. While higher C levels in temperate grassland are a common conclusion (Zhao *et al*., 2007; Hu *et al*., 2008; Zhao *et al*., 2009; Katsuno, *et al*., 2010), results for total N in temperate grassland sites were both higher than (Zhao *et al*., 2007), and similar to, plantation sites (Zhao *et al*., 2009).

2.1.2 Pastureland focus

Studies on eucalypt afforestation in Australia initially focused on the impact on the hydrological cycle (*e.g.* Sahin and Hall, 1996). More recent research focused on the impacts on N mineralisation (O'Connell *et al*., 2003; Mendham *et al*., 2004) and C and N stocks (Turner and Lambert, 2000; Guo *et al*., 2008; Kirschbaum *et al*., 2008) in pastureland soils following the establishment of both pine and eucalypt plantations. Australia is one of the few regions where studies have reached a consistent conclusion that both N and C levels decline in pastureland soils post afforestation. In New Zealand, investigations into the impact of low density tree planting on microclimate in pasturelands (*e.g.* Hawke and Wedderburn, 1994) were driven by the agricultural shift toward agroforestry. While there was little difference in observed air temperature, soil surface temperature was lower in the pine plantation across all seasons. Research then focused more on the impact of *Pinus radiata* on pasture (Parfitt *et al*., 1997; Groenendijk *et al*., 2002; Tate *et al*., 2007; Macdonald *et al*., 2009; Singh *et al*., 2009), with grassland (Alfredsson *et al*., 1998; Chen *et al*., 2003) and shrubland (Tate *et al*., 2007) receiving less attention. Total C and N in a pastureland were higher than in an adjacent pine plantation, (Macdonald *et al*., 2009). So too were pH (Groenendijk *et al*., 2002), moisture levels (Parfitt *et al*., 1997), Mg and sodium (Na) (Parfitt *et al*., 1997). Within the top 5cm of soil, Al, C, N, Mg and K levels were all higher in grassland than an adjacent fir plantation (Alfredsson *et al*., 1998). Soil surface temperature data over both the short term (Scott *et al*., 2006) and long term (Chen *et al*., 2003) indicated a seasonal variation with higher values recorded in the pine plantation in winter and lower values from spring through to autumn.

2.1.3 Silvicultural agroforestry and indigenous forest focus

During the 19th century, deforested and degraded landscapes were the target for restoration programs in France (Porté *et al*., 2004). In the Mediterranean regions of Spain and Greece the well-adapted and often traditional silvo-pastoral system formed the basis for research into direct tree-grass interactions (Silva-Pando *et al*., 2002; Gea-Izquierdo *et al*., 2009). The overall impact of the trees on the grassland is a balance of both facilitation and competition. In general, it was found that trees in agroforestry systems increase nutrient content due to biomass, adsorption, and subsequent deposition, of certain atmospheric ions, leaching and additional animal activity (Gea-Izquierdo *et al*., 2009). Gea-Izquierdo *et al*. (2009) conclude that trees decrease light availability and soil moisture, and increase soil water holding capacity. They also found that the physical tree canopy results in redistribution of precipitation, lowering of the average soil surface temperature and decreases the range between surface temperature maxima and minima. Silva-Pando *et al*. (2002) reached a similar conclusion as higher minimum temperatures were recorded at the start and end of the growing season under pine canopy than in the open.

2.2 Research themes

When considered in its entirety, afforestation research has followed three major themes:

The first theme is the evaluation of the magnitude of the impact of afforestation on soil and microclimate. This theme is evident from the first studies on afforestation and continues to be pertinent today. One of the earliest studies on soil chemical properties was by Percival *et al.* (1984a) where the nutrient status of cropland soil, post plantation establishment, was of interest. The microclimatic affects of pine trees and the implications for livestock were investigated by Percival *et al.* (1984b) and continue to be a focus as agroforestry develops (Feldhake, 2001; Koukoura and Kyriazopoulos, 2007; Gea-Izquierdo *et al.*, 2009). Agroforestry studies focus on a variety of parameters within air microclimate, soil microclimate and soil physical and chemical properties.

The second theme concerns an understanding of the mechanisms involved in the observed change. This theme is evident when research narrowed its focus on a select few soil parameters in the late 1990s and early 2000s where the aim was to quantify the impact of afforestation on these parameters as well as to understand the dynamics of the change. Phosphorous (Chen *et al.*, 2000, 2003; Zhao *et al.*, 2007; Zhao *et al.*, 2009), acidity (Jobbágy and Jackson, 2003), nitrogen, (Parfitt *et al.*, 1997; Farley and Kelly, 2004), organic matter (Mendham *et al.*, 2004; Lima *et al.*, 2006), soil organic carbon (Parfitt *et al.*, 1997; Guo *et al.*, 2008; Hu *et al.*, 2008; Kirschbaum *et al.*, 2008; Katsuno *et al.*, 2010), trace gas fluxes (Tate *et al.*, 2007; Singh *et al.*, 2009), soil fungal and bacterial communities (Macdonald *et al.*, 2009) and temperature (Scull, 2007) are the parameters that have received attention. One of the major results of the focus on a few soil parameters is in-depth information on the magnitude and mechanisms of the impact that plantations have on soil.

The third theme concerns the consequences of afforestation. This theme became evident when researchers, recognising an abundance of information in the late 1990s and early 2000s, focused on the indirect impact of plantations. Initially, studies considered how the changes in plantation soils affect their ability to sustain plant growth (Alfredsson *et al.*, 1998) and soil fertility (Lilienfein *et al.*, 2000). The focus thereafter shifted to considering the boundary effect on areas adjacent to plantations, examples are studies on the impact on grassland diversity (Allan *et al.*, 1997; van Wesenbeeck *et al.*, 2003), ecosystem processes and services (Farley *et al.,* 2004) and native forest fragment survival (Denyer *et al.*, 2006). Both van Wesenbeeck *et al.* (2003) and Allan *et al.* (1997) concluded that grassland diversity and species composition decrease in response to afforestation. Farley *et al.* (2004) argue that, although plantation forestry in páramo grasslands may provide economic benefits, the ecosystem services of soil C storage and water retention are negatively affected. Denyer *et al.* (2006) found that the presence of pine plantations adjacent to native forest fragments decreases light intensity and air temperature at the edge of the native forest, thus, interior conditions are improved within the native forest. However, when the plantation is harvested and replanted, the microclimate buffering at the edge of the native forest is much reduced which leads to an abnormal light and temperature dynamic.

The investigation of the impacts of afforestation, and their associated mechanisms, has involved many biomes within a variety of climates. A focus on similar microclimate variables and soil properties has been maintained, although it has been driven by unique region-dependant objectives. While there are similarities in the research themes and the parameters which have been studied, there are some key differences, requiring further investigation. One of these differences is in research approach.

2.3 Research approaches

Instrumentation, size and complexity of datasets, logging intervals, site selection, site layout, soil sampling and soil analysis make up the core of research methodology for studies on soil and microclimate in plantations. Each factor plays a role in determining whether or not one study may be reliably compared to another.

The site selection method, size and number of sites differ across all studies on the impact of afforestation on microclimate and soil. Methods vary from two paired plots in a plantation and adjacent pasture (Singh *et al.*, 2009), to five plots in each vegetation type (Zhao *et al.,* 2009), to one research site in each vegetation type (see Groenendijk *et al.,* 2002 and Chen *et al.,* 2003). The age of plantations in each study varies from one year to more than a century (Table 2.1). Some studies include a cross section of age classes (*e.g.* Mendham *et al.*, 2004; Lima *et al.*, 2006; Zhao *et al.*, 2007) and show that plantation age has an influence on results. Site selection and layout is thus unique to each study.

Measurement of the microclimate, within plantation and grassland sites, ranges from once a month for seven months (Parfitt *et al.*, 1997) to 3 years (Hawke and Wedderburn, 1994; Guo *et al.*, 2008) with a common period being one growing season (Table 2.1). Such a dataset can provide a basis from which to draw conclusions regarding seasonal responses. On the contrary, relatively few soil sampling methods have involved sampling on more than one occasion (Table 2.1). Where soil sampling was more frequent, evidence of variation both within and between seasons was observed (*e.g.* Hart *et al.*, 1993; Chen *et al.*, 2003; Cao *et al.*, 2007; McKinley *et al.*, 2008). Soil sampling across seasons provides useful insight into nutrient fluxes between and within the growing seasons of grassland and plantation. Hart *et al.* (1993) and McKinley *et al.* (2008), for example, were able to comment on the seasonal soil N cycle and Parfitt *et al.* (1997) found measurable differences in nutrient concentrations and fluxes across one season. In addition, temperature and moisture variation due to seasonal changes has a disparate influence on soil chemical processes across plantation and grassland sites (Zhao *et al.*, 2009). It is clear, therefore, that comparing soil chemical properties of afforested sites with adjacent grassland sites, based on a soil dataset from one season, may not reflect the overall impact of afforestation.

A variety of instruments and sensors have been selected to take measurements in microclimate studies (Table 2.2). Different probe types were used to measure air temperature and soil temperature in eight separate studies (Table 2.2). The sensor heights above ground and depths below the soil surface are also inconsistent in these studies. Logging intervals range from 10 seconds to 24 hours to discrete, once-off measurements (Table 2.2). Graphical representation of data in some studies contains daily minimums, maximums and means (*e.g.* Hawke and Wedderburn, 1994) while others contain raw data (*e.g.* Chen *et al.*, 2003).

The depth at which soil samples are taken varies greatly from study to study (Table 2.1). Some methods involved sampling from equidistant points in the soil horizon at 6–15cm intervals (Yeates, 1988; Jaiyeoba, 1998; Lilienfein *et al.*, 2000; Hu *et al.*, 2008; Kirschbaum *et al.*, 2008; Katsuno *et al.*, 2010). In some cases, the samples for each horizon, or for each site, were bulked to form one sample (Parfitt *et al.*, 1997; Alfredsson *et al.*, 1998; Chen *et al.*, 2000; Groenendijk *et al.*, 2002; Lima *et al.*, 2006; Scott *et al.*, 2006). Other approaches entailed the use of a sample from specific depth ranges of 0–5cm, 0–10cm or 10–15cm, some of which were bulked to form one sample (Chen *et al.*, 2003; Zhao *et al.*, 2009). Hydraulic soil coring has also been used to sample up to 100cm in depth (Guo *et al.*, 2008).

The methods selected for the analysis of soil chemical properties are also not consistent across studies (Table 2.3). An auto analyser is a popular choice for the determination of total carbon and nitrogen and phosphorous (Table 2.3), although extraction methods for phosphorous differ between studies. Different ratios of soil and water were used for the determination of pH (Table 2.3). When soil moisture is not determined *in situ*, the gravimetric analysis method is consistently selected across studies.

Table 2.2: Sensors used, sensor height or depth (where * = no radiation shield, ** = presence of shield not specified) and monitoring interval for certain microclimate parameters

Parameter	**Reference**	**Sensor/Method**	**Sensor Height/Depth (cm above/below soil surface)**	**Monitoring Interval**
Air temperature	Selleck and Schuppert, (1957)	Not specified	20**	Not specified
	Hawke and Wedderburn (1994)	Not specified	0, 45, 50	24 hour max and min
	Silva-Pando *et al.* (2002)	LICOR 1000–15 Temperature Sensors	150**	1 min, hourly mean
	Porté *et al.* (2004)	Pt 100Ω probe	10* and 200	15 min (stands) and 1 hour (open area)
	Gea-Izquierdo *et al.* (2009)	Unspecified probe	0** and 30**	24 hour max and min
Humidity	Silva-Pando *et al.* (2002)	LICOR LI–190SA Quantum Sensors	0	1 minute, hourly mean
Photosynthetically active radiation	Porté *et al.* (2004)	Unspecified Pyranometer	200	15 mins (stands) and 1 hour (open area)
Solar irradiance	Chen *et al.* (2003)	Thermocouples	0–5	10 min
Wind	Hawke and Wedderburn (1994)	Cup anemometer	50	24 hour wind run
	Porté *et al.* (2004)	Unspecified anemometer	Not specified	1 hour

Soil temperature	Hawke and Wedderburn (1994)	Not specified	10, 30	Not specified, seasonal average
	Parfitt *et al.* (1997)	Not specified	10, 20	Not specified
	Porté *et al.* (2004)	Pt 100Ω probe	10	15 mins (stands) and 1 hour (open area)
	Guo *et al.* (2008)	Unspecified probe	5, 20, 45	24 hour max, min and mean
Soil moisture	Parfitt *et al.* (1997)	Not specified	10, 20	Not specified
	Farley *et al.* (2004)	Gravimetric analysis	n/a	15 min (stands) and 1 hour (open area)
	Scott *et al.* (2006)	Gravimetric analysis	10, 20	Once off
	Tate *et al.* (2007)	Moisture release at –2.5, –5 and –10kPa	10	Once off
	Guo *et al.* (2008)	Time domain reflectometry using 15cm probes	15	Not specified
	Singh *et al.* (2009)	Gravimetric analysis	10	Once off
	Zhao *et al.* (2009)	Gravimetric analysis	20	4 samples separated by 2 months, 1 month and 2 months

Table 2.3: Analytical methods used for soil chemical parameters

Parameter	**Analytical Method**	**Reference**
Calcium	Atomic absorption spectrometer, using the following extractions: Strong acid digestion Ammonium acetate extraction Barium chloride extraction	 Parfitt *et al.* (1997) Alfredsson *et al.* (1998) Lilienfein *et al.* (2000)
	Inductively coupled plasma emission spectrometry - ammonium acetate extraction	Jobbágy and Jackson (2003)
Total Carbon	Mass spectrometry	Alfredsson *et al.* (1998)
	Combustion in auto analyser	Chen *et al.* (2000) Groenendijk *et al.* (2002) Chen *et al.* (2003) Jobbágy and Jackson (2003) Farley *et al.* (2004) Mendham *et al.* (2004) Lima *et al.* (2006) Tate *et al.* (2007) Kirschbaum *et al.* (2008) Macdonald *et al.* (2009) Singh *et al.* (2009)

	Walkley-Black method (H2SO4–$K_2Cr_2O_7$ oxidation)	Ndala *et al.* (2006) Zhao *et al.* (2007) Hu *et al.* (2008) Zhao *et al.* (2009)
Organic Matter	Loss on ignition	Van Wesenbeeck *et al.* (2003)
	Sodium iodide extraction, centrifuged, siphoned, dried and weighed	Lima *et al.* (2006)
Magnesium	Plasma emission spectrometry	Jobbágy and Jackson (2003)
	Atomic absorption spectrometry Strong acid digestion Ammonium acetate extraction Barium chloride extraction	 Parfitt *et al.* (1997) Alfredsson *et al.* (1998) Lilienfein *et al.* (2000)
Total Nitrogen	Mass spectrometry	Alfredsson *et al.* (1998)
	Combustion in auto analyser	Parfitt *et al.* (1997) Chen *et al.* (2000) Chen *et al.* (2003) Jobbágy and Jackson (2003) Farley and Kelly (2004) Guo *et al.*(2008) Kirschbaum *et al.* (2008) Macdonald *et al.* (2009) Singh *et al.* (2009)
	Steam distillation after Kjeldahl digestion	Zhao *et al.* (2007, 2009)
	Colormetric analysis with an autoanalyser Digestion in sulphuric acid and hydrogen peroxide mixture Digestion in sulphuric acid Persulphate oxidation	 Mendham *et al.* (2004) Ndala *et al.* (2006) Tate *et al.* (2007)
Extractable Nitrogen	Colormetric analysis with an autoanalyser Potassium Chloride extraction Potassium sulphate extraction	 Tate *et al.* (2007) Singh *et al.* (2009) Farley and Kelly (2004) Ndala *et al.* (2006)
Extractable Phosphorous	Colormetric analysis with an autoanalyser Deionised water extraction Olsen extraction – sodium carbonate Bray 1 extraction – ammonium fluoride and hydrochloric acid	 Van Wesenbeeck *et al.* (2003) Chen *et al.* (2000) Chen *et al.* (2003) Zhao *et al.* (2007, 2009) Farley and Kelly (2004)
Total P	Inductively coupled plasma spectrometry – digested in nitric and perchloric acid	Farley and Kelly (2004)
	Colormetric analysis with an autoanalyser – digested in Sulphuric acid	Ndala *et al.* (2006)

pH	Soil:deionised water ratio of 1:2.5	Parfitt *et al.* (1997) Chen *et al.* (2000) Chen *et al.* (2003) Ndala *et al.* (2006) Tate *et al.* (2007) Zhao *et al.* (2007) Macdonald *et al.* (2009) Singh *et al.* (2009) Zhao *et al.* (2009)
	Soil:deionised water ratio of 1:5	Van Wesenbeeck *et al.* (2003)
	Soil:deionised water ratio 1:1	Groenendijk *et al.* (2002) Farley and Kelly (2004)
	Solution of calcium chloride	Alfredsson *et al.* (1998)
	Measured *in situ* with standard pH electrode	Lilienfein *et al.* (2000)
Potassium	Atomic absorption spectrophotometer Strong acid digestion Ammonium acetate extraction De-ionised water extraction Barium chloride extraction	 Parfitt *et al.* (1997) Alfredsson *et al.* (1998) Lilienfein *et al.* (2000) Van Wesenbeeck *et al.* (2003)
	Inductively coupled plasma emission spectrometry – ammonium acetate extraction	Jobbágy and Jackson (2003)

Datasets, site layout, soil sampling, instrumentation and soil analysis thus vary across studies. This has resulted in a situation where research approaches, in a substantial body of literature, are unfortunately inconsistent, which poses a challenge in understanding the general impact of afforestation on specific microclimate and soil properties. Nevertheless, given what data are currently available, some general conclusions can be drawn regarding the impact afforestation has on microclimate and soil.

2.4 Impact on microclimate

Microclimate is a term encompassing the climatic conditions measured in localised areas near the earth's surface (Chen *et al.*, 1999) and within the soil profile. The microclimate factors which have been monitored include air temperature, wind speed, vapour pressure deficit, humidity, solar irradiance, soil temperature and soil moisture.

2.4.1 Impact on aboveground microclimate

Ambient air temperature is influenced by the radiative properties of the atmosphere, humidity, wind currents, surface albedo, solar angle and shading (Willmott, 1987). Afforestation has an effect on all these except solar angle. Temperature is an important factor as it affects plant photosynthesis, respiration and germination (Benavides *et al.*, 2009). Extremes in air temperatures up to 2m above the surface are moderated by afforestation at both a diurnal (Selleck and Schuppert, 1957; Gea-Izquierdo *et al*., 2009) and seasonal scale (Silva-Pando *et al*., 2002; Porté *et al*., 2004), but not in all cases (Hawke and Wedderburn, 1994).

Wind speed has been of more interest as a factor that affects livestock mortality. Wind reduction contributes to reducing thermal strain on livestock and thus improves their survival. Wind speed in plantations can be reduced by up to 78% of wind speed adjacent open areas (Hawke and Wedderburn, 1994). Unexpectedly weak air temperature differences have been observed between plantation and open areas in areas where high wind speeds, and therefore air mixing, are common (Porté *et al.,* 2004). Weaker air temperature differences would also lead to weaker vapour pressure deficit differences (Porté *et al.,* 2004) and the movement of moisture during air mixing would decrease humidity differences.

Vapour pressure deficit (VPD), which is a direct function of humidity and temperature, is higher outside of afforested areas (Porté *et al*., 2004). The VPD equation is such that higher temperatures and unchanging humidity values result in a higher VPD. In many cases, VPD differences therefore occur more as a result of differences in temperature than in humidity (Porté *et al*., 2004). Selleck and Scuppert (1957) found humidity to be moderated within a pine forest with results showing lower maxima and a higher minima, but similar means to adjacent open prairies, over a period of 17 days in spring.

Solar irradiance has been suggested as the driver of variations in other microclimatic elements such as air and soil temperature, relative humidity soil moisture. Photosynthetically active radiation is believed to be the main factor affecting productivity when soil nutrients and water are freely available (Benavides *et al.*, 2009). Both quantity and quality of solar irradiance affect physiological and physical processes. Solar irradiance reduction varies over seasons and with aspect (Benavides *et al.*, 2009) as, during the southern hemisphere winter, south-facing slopes experience a greater solar irradiance reduction than north-facing slopes.

2.4.2 Impact on soil microclimate

Soil surface temperature is strongly dependent on incident solar radiation and soil moisture content (Feldhake, 2001). Soil temperature under canopy is always lower than in grassland in temperate regions (Hawke and Wedderburn, 1994; Parfitt *et al*., 1997; Scull 2007; Guo *et al*., 2008), and mean annual soil temperature can differ by up to 4ºC between soils under canopy and soils under grassland (Guo *et al.*, 2008). However, soil temperatures under dense grass cover can be similar to those under a forest canopy (Holl, 1999). In addition to significant absolute differences, ranges of daily soil temperature are smaller under plantation canopy than under grassland (Silva-Pando *et al.*, 2002; Porté *et al.*, 2004; Gea-Izquierdo *et al.*, 2009).

In general, soil moisture is significantly higher in open pasture or grassland than under plantation in both temperate (Parfitt *et al*., 1997; Tate *et al*., 2007; Macdonald *et al*., 2009) and tropical regions (Farley *et al*., 2004) but seasonal differences have been reported. Soil moisture was found to be much higher in grassland than in an adjacent pine plantation in dry seasons, but at similar levels during the rainy season (Zhao *et al*., 2009). Gea-Izquierdo *et al.* (2009) found that soil that is closer to a tree will have a lower soil moisture value than soil further from a tree. While the specific tree species may also have an influence on moisture content due to shading properties, transpiration rates and photosynthetic demands (Menezes *et al*., 2002). This would be evident in a comparison of soils under pine trees, which are relatively dormant during the dry season, and under eucalypt trees, which continue to be physiologically active throughout the year (Dye *et al.*, 1995).

2.5 Impact on soil physical and chemical properties

Soil acidity is an indicator of lower cation exchange capacity and a lowered nutrient storage capacity (McFee *et al.*, 1976). The use of deionised water is the most common method for pH determination but others, such as the use of calcium chloride solution, may provide better insight into pH variations (Binkley, 1995). Three mechanisms for soil acidification were proposed by Jobbágy and Jackson (2003):

(i) organic acid produced by plant litter at the soil surface

(ii) carbonic acid from soil respiration at the root level

(iii) the sequestration and redistribution of cations from the soil profile to the soil surface through plant litter.

Maximum acidity is dependent on which mechanism is driving acidification and will thus be detected at the soil surface, at root level or deeper in the soil profile. A decline in pH has been reported across many studies where grassland is converted into plantation. This acidification is consistent across temperate pine sites (Parfitt *et al*., 1997; Alfredsson *et al*., 1998; Lilienfien *et al*., 2000; Groenendijk *et al*., 2002; Scott *et al*., 2006; Tate *et al*., 2007; Zhao *et al*., 2007; Macdonald *et al*., 2009; Singh *et al*., 2009) and tropical eucalypt sites (Jobbágy and Jackson, 2003) and values rarely differed by more than one pH unit. Exceptions are noted by van Wesenbeeck *et al.* (2003) and Zhao *et al.* (2009) who found no significant differences in pH when comparing grassland to tropical *Pinus patula* plantation and temperate *Pinus sylvestris* var. *mongolica* plantation respectively.

Carbon sequestration by plantations gained more interest following the implementation of the Clean Development Mechanism, under the Kyoto Protocol to the United Nations Framework Convention on Climate Change. Developed countries could meet carbon emission reduction targets through reforestation or afforestation in developing countries. The factors affecting soil organic carbon (SOC), following afforestation, are: site preparation, previous land use, climate, soil clay content and site management (Paul *et al.*, 2002). SOC analysis in most studies is performed on soil from 0–15cm depth. A decline in SOC in pine plantations younger than 30 years is common in many regions including both tropical (Farley *et al.*, 2004) and temperate (Parfitt *et al.*, 1997; Alfredsson *et al.*, 1998; Groenendijk *et al.*, 2002; Chen *et al.*, 2003; Scott *et al.*, 2006; Zhao *et al.*, 2007; Guo *et al.*, 2008; Hu *et al.*, 2008; Kirschbaum *et al.*, 2008; Macdonald *et al.*, 2009; Singh *et al.*, 2009). However, Paul *et al.* (2002) concluded that, following afforestation, SOC decreases for up to 30 years then begins to increase. Insignificant differences in SOC were found between 20–year–old pine and savanna in Brazil (Lilienfein *et al.*, 2000) and between 22–year–old pine and grassland in China (Zhao *et al.*, 2009).

Cations are essential nutrients for plants. Potassium (K) is used by plants for pH regulation and for maintaining water levels in tissue (Johnson, 1992). Magnesium (Mg) is used in pH regulation (Marschner, 1986) and photosynthesis (Johnson, 1992) and Calcium (Ca) forms a major component of permanent plant tissue (Cole and Rapp, 1981). Cation concentrations are expected to decrease as not all cations taken up by trees are returned to soil in litter and rot detritus (Attiwell and Adams, 1993). This fact is evident in many studies involving Ca (Parfitt *et al.*, 1997) and K (Parfitt *et al.*, 1997; Alfredsson *et al.*, 1998; Van Wesenbeeck *et al.*, 2003) analysis under both temperate and tropical pine regions, and K, Ca and Mg under Eucalypt in a dry sub-humid region of Nigeria (Jaiyeoba, 1998). However, Mg and sodium (Na) concentrations have also increased under pine (Alfredsson *et al.*, 1998; Parfitt *et al.*, 1997; Lilienfein *et al.*, 2000) and variations, with soil depth, have been recorded for Ca, Mg, K and Na (Parfitt *et al.*, 1997; Lilienfein *et al.*, 2000). Cation availability could be higher in lower rainfall areas due to an uptake from lower horizons and subsequent deposition on the surface in litterfall (Alfredsson *et al.*, 1998). Cation levels may likewise be increased in coastal areas by the interception of sea salts by the plantation canopy (Alfredsson *et al.*, 1998).

Nitrogen (N) is an important plant nutrient and suboptimal levels restrict plant growth. N availability is determined by the N cycle, which is made up of nitrification and denitrification, mineralisation and N fixation. Nitrification and denitrification are performed by the *Nitrosomonas* bacteria and N fixation is a process that only a few plants are able to accomplish. The rate of N mineralisation involves the decomposition of organic matter into a mineral form of N, which is available for plant uptake. The impact of a plantation on the rate of N mineralisation is of interest as it is often the limiting step in supply of N to a plant (Louw and Scholes, 2002) and consequently will reduce N availability when negatively affected. Investigations into N availability have thus focused on both total N and N mineralisation rates. Pine afforestation has caused a significant decrease in total N compared to adjacent grassland in dry sub-humid (Jaiyeoba, 1998), tropical (Farley and Kelly, 2004) and temperate regions (Alfredsson *et al.*, 1998; Parfitt *et al.*, 1997; Groenendijk *et al.*, 2002; Chen *et al.*, 2003; Scott *et al.*, 2006; Tate *et al.*, 2007; Zhao *et al.*, 2007; Guo *et al.*, 2008; Macdonald *et al.*, 2009). Parfitt *et al.* (1997), Chen *et al.* (2003) and Hart *et al.* (1993) analysed total N in soil samples taken during different seasons and observed differences between the seasons. Eucalypts (Mendham *et al.*, 2004) have been shown to reduce N mineralisation and this may be due to the lower soil pH, cation exchange capacity and temperatures in plantation soil. Lower temperatures under canopy may contribute to lower nutrient cycling rates than that of adjacent, unshaded grassland. However, Ndala *et al.* (2006) found that during spring plantation soils had more rapid rates of N mineralisation than adjacent soils under grassland. Ndala *et al.* (2006) believed that the addition of moisture after a long dry winter stimulated N mineralisation.

Phosphorous (P) is required by plants for metabolic processes, cell division and respiration (Terry and Ulrich, 1973). Studies in the temperate regions of China and New Zealand indicate that P is generally higher in grasslands (Chen *et al.*, 2000, 2003, 2008; Zhao *et al.*, 2007, 2009; Davis, 1998; Ndala *et al.*, 2006). Regional soil type or climate may have an influence on the prevalence of P as Farley and Kelly (2004) found no significant difference on volcanic andisols in tropical Ecuador. The method used to extract P has been shown to have an impact on results, as Holl (1999) found resin-extracted P to be higher in a tropical forest but bicarbonate-extractable P was not significantly different to pasture. Many studies found that plant-available P is higher in grasslands than plantations (Farley and Kelly, 2004; Chen *et al.*, 2000, 2003; Zhao *et al.*, 2007, 2009), although Davis (1998) found this to be true only for plantations older than 15 years. Inorganic P was lower in grasslands in some studies (Chen *et al.*, 2000, 2003) and higher in others (Zhao *et al.*, 2007, 2009). Farley and Kelly (2004) found extractable P to be higher in plantations older than 15 years. The chemical nature of P dynamics in soil following conversion of grassland to coniferous plantation is not yet fully understood (Chen *et al.*, 2008).

2.6 Summary

Afforestation research has its roots in fragmentation research, from where it progressed into silvicultural agroforestry studies. Subsequent research was dependant on which biomes were affected by afforestation and this lead to a split into the three regional focus areas, namely:

- grassland and tropical forest
- pastureland
- silviculture and temperate forest.

Although afforestation research has developed in response to region specific drivers, all published studies fall into one of three major themes. The evaluation of the magnitude and impact of afforestation on soil and microclimate specifically was the first theme to develop and spans more than two decades. The focus of the second theme is on the mechanisms responsible for changes in soil parameters and developed in the late 1990s. In tandem with this theme, a third theme emerged which focussed on a better understanding of the indirect impacts of afforestation.

One major weakness with all of these research themes is the lack of consistency in approaches to research methodology. This includes the time period within which data are gathered, the number of data points obtained, the number and location of sites, the number of soil samples, soil sampling techniques, and soil analysis techniques. These all contribute to a low confidence in any conclusions based on a comparison of results from different studies. It may thus be necessary to consider developing a standardised approach to research in this field.

More specific research issues exist regarding soil chemical analysis and P dynamics. It is not yet clear which techniques are better to analyse a certain soil chemical property. Research into the suitability and accuracy of certain techniques is critical in order to obtain meaningful data. Mechanisms responsible for P variations in soil are not yet fully understood. Dynamics of chemical and physical changes in soil need to be well understood before management interventions, where necessary, can be planned.

Despite the above challenges, afforestation has demonstrated a marked impact on both microclimate and soil properties. Because microclimate is a determinant of ecological patterns in both plant and animal communities (Chen *et al*., 1999), changes in microclimate cause changes in the growth and mortality processes of organisms, and also influence plant regeneration and growth, soil respiration and nutrient cycling (Chen *et al*., 1999). A shift in microclimate can affect insect, mammalian and vegetation diversity (Bredenkamp *et al*., 1999; Foord *et al*., 2003; Johnson *et al*., 2002), which reduces the total biodiversity and leads to loss in real and potential ecosystem services.

Changes in soil properties may also affect the sustainability of future plantations (Mendham *et al*., 2002) as well as suitability for other agricultural purposes. Afforestation may have inherent trade-offs as a potential gain for climate change through above-ground carbon sequestration which may be offset by a negative impact on soil carbon storage and water retention (Farley *et al*., 2004). Specific knowledge of the changes in soil properties following afforestation is required both for effective plantation management and rehabilitation.

2.7 Future studies and the role of this dissertation

The impacts of afforestation on soil and microclimate must remain a critical focus as specific implications of the impacts of afforestation will ultimately guide decision makers on the future of plantations. Therefore, there is a need for a consistent and clear understanding of the impact of plantations on soil and microclimate. The focus of future research should thus:

- avoid bulking soil samples
- conduct a comprehensive and consistent analysis of concentrations of a full range of soil chemicals
- include seasonal measurements of air microclimate and soil chemistry
- assess both mean results and seasonal results
- understand the impacts which occur adjacent to the plantation.

This study seeks to investigate the potential impact afforestation has on soil and microclimate in adjacent grassland fragments. Air microclimate data and soil microclimate and chemistry data will encompass four seasons and will be assessed at an individual, mean and seasonal level. Soil chemical analysis will be performed on individual soil samples and analytical techniques will be taken into account when discussing results. Alignment with the suggested afforestation research focus areas is demonstrated in the following chapter (Chapter 3), where the study area is introduced, followed by Chapter 4 which presents the study methods used to meet this study's specific research objectives.

CHAPTER 3: STUDY AREA

Groenvaly ("Green Valley") is located in the Mpumalanga province (Fig. 3.1), the largest timber growing province of South Africa (DAFF, 2010). At an altitude of up to approximately 1700masl, Groenvaly (25°51'S 30°45'E) is situated on the westerly aspect of the single most prominent geomorphic feature of the subcontinent – the Drakensberg escarpment. This sub-tropical region has hot wet summers and cool dry winters and is home to montane grassland. Of all South African biomes, grassland is the most transformed by human activity (Macdonald, 1989) and the montane grassland, in particular, is known to contain large numbers of endemic species (Matthews *et al.*, 1993). It was estimated in 1995 that 2.7% of the grassland biome was planted with commercial trees (DWAF, 1995); with montane grasslands in high rainfall areas remaining under threat from large scale commercial afforestation (Armstrong and van Hensbergen, 1997). More recent data on the percentage of the grassland biome planted with commercial trees are not available, however, in 2009, over 519 000 ha of Mpumalanga was afforested and represents more than 40% of the total forested area of South Africa (DAFF, 2010). Pine plantations constitute 59% and 51% of the commercial forested area of Mpumalanga and South Africa respectively.

3.1 Climate

Regional climate data were obtained, courtesy of the Agricultural Research Council, from an automated weather station located at Elukwatini (S 26°2', E 30°47') 20km south of the study area. Mean annual rainfall between 2003 and 2011 was 645 mm and 95.1% of the rain was recorded between September and April (Fig. 3.2). Average relative humidity fluctuates between 52.5% in September and 72.1% in January (Fig. 3.2). Mean annual air temperature is 19°C (Fig. 3.3). The warmest month is February with an average daily maximum of 29.72°C (Fig. 3.3) and the coolest month is July with an average daily minimum of 5.13°C (Fig. 3.3). October is the windiest month with an average wind speed of 1.77m/s and is only slightly higher than the calmest average of 1.08m/s in July (Fig. 3.4). Solar irradiance peaks in

February, with an average of 22.0 MJ/m^2, and declines in June with an average of 10.0 MJ/m^2 (Fig. 3.4).

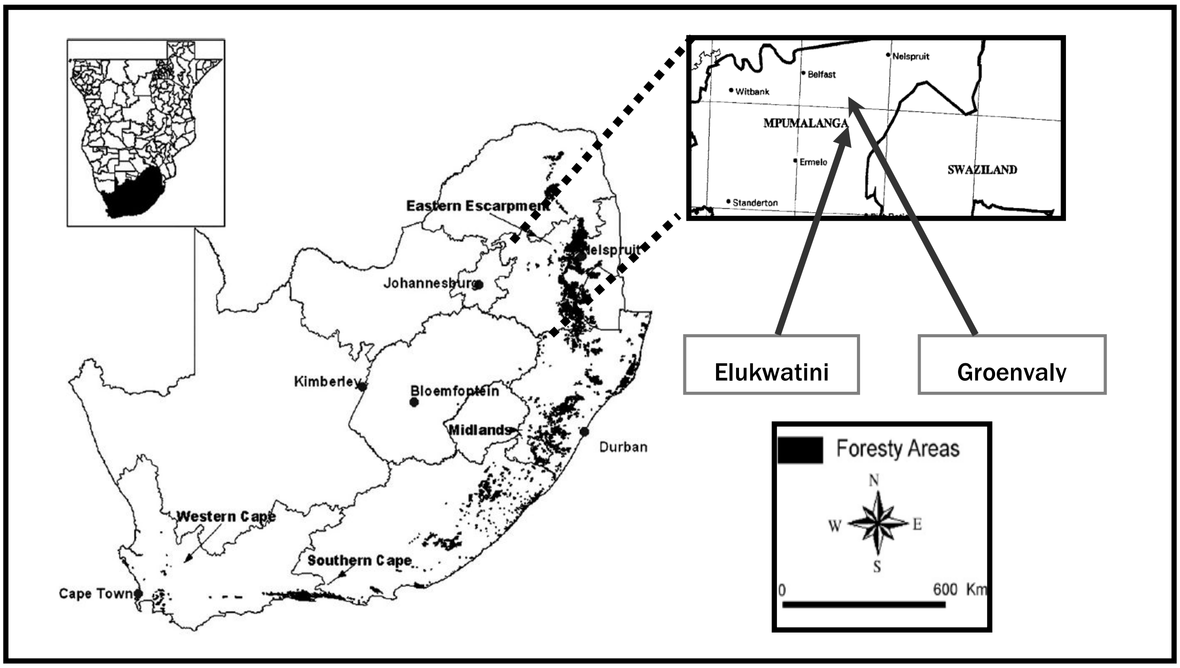

Figure 3.1: Location of forestry areas in southern Africa, the Groenvaly study area and the Elukwatini weather station in Mpumalanga. The Drakensburg escarpment follows the approximate layout of the forestry areas in the east of South Africa. (Modified from: Ndala *et al.*, 2006 and Turner, 2000)

3.2 Topography, soils and geology

Groenvaly is located on the Nelshoogte Schist Belt (Fig. 3.5). This belt consists of a succession of massive and pillowed komatiitic basaltic lavas, interlayered with peridotitic lavasand, a few minor siliceous schists (Fig. 3.6) and banded chert bands (Anhaeusser, 1981). The study area is located on undifferentiated basaltic komatiites, metatholeiites, mafic and ultramafic tuffs and hornblende-actinolite-chlorite-carbonate schists (Anhaeusser, 2001). There are two diabase intrusions; one forms the ridge to the north of the study area and the other is parallel to the river in the south. Two north-south dolerite dykes are present; one to the east of the study area and the other forms the western border of the Groenvaly plantation. The dykes intersect the aforementioned diabase intrusions.

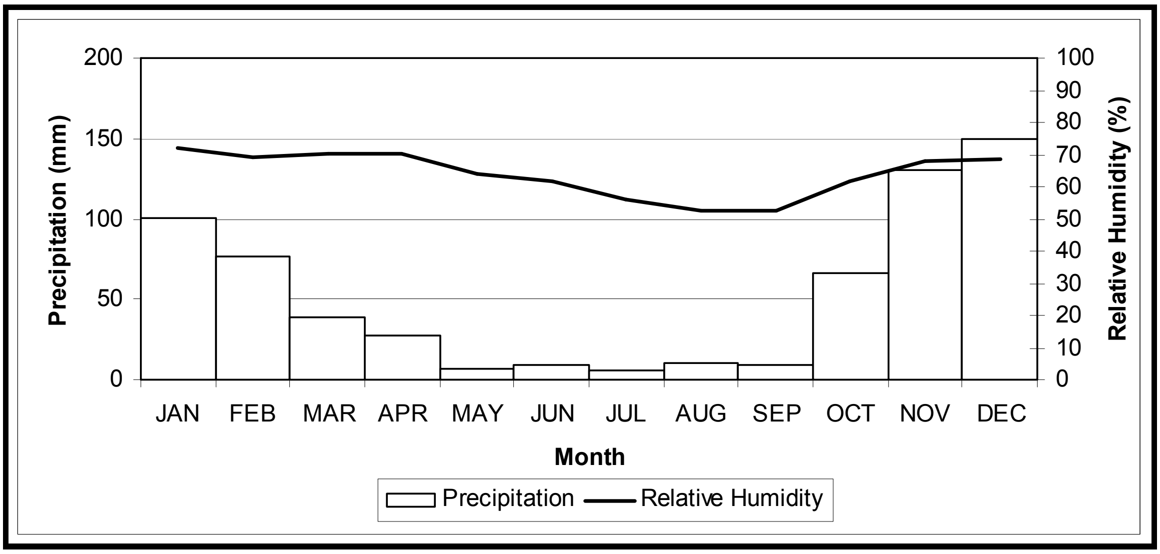

Figure 3.2: Mean monthly precipitation and relative humidity for the period February 2003 – January 2011 (Raw data source: Elukwatini weather station (26°2'S, 30°47'E), courtesy of the Agricultural Research Council)

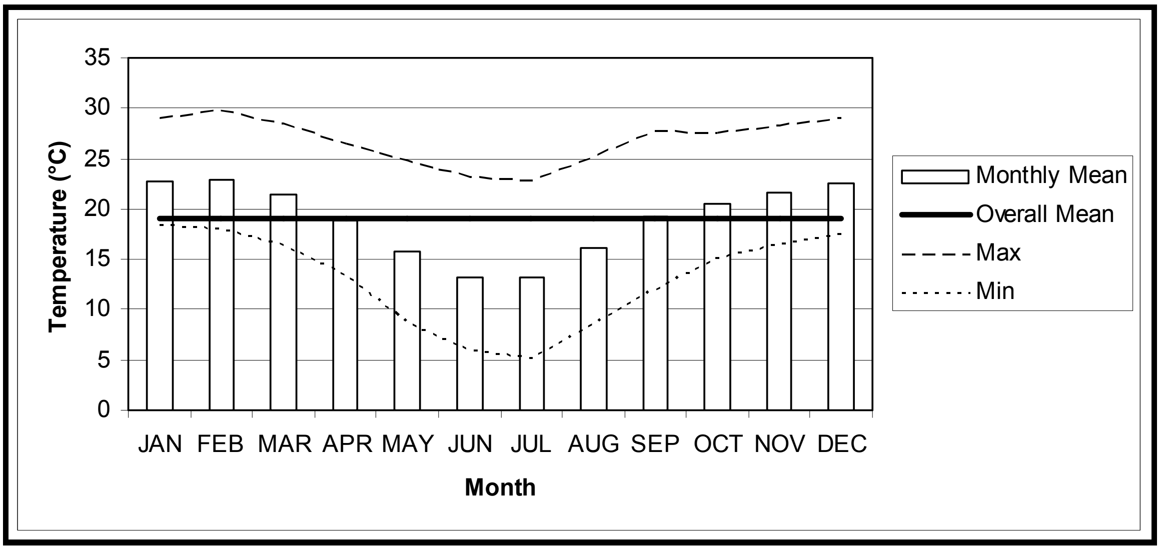

Figure 3.3: Mean monthly daily maximum, daily minimum and overall mean temperatures for the period February 2003 – January 2011 (Raw data source: Elukwatini weather station (26°2'S, 30°47'E), courtesy of the Agricultural Research Council)

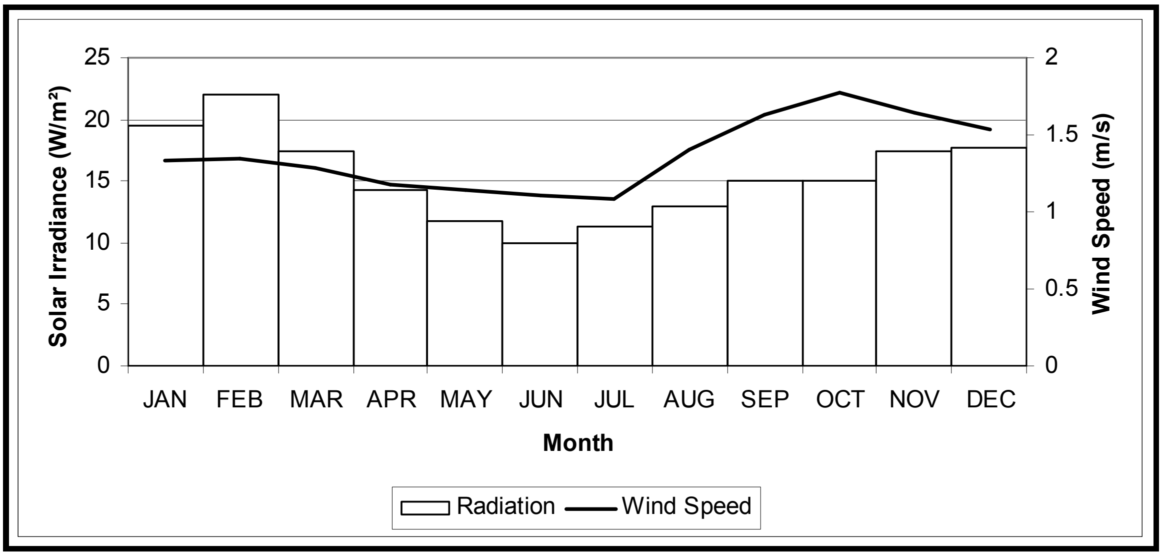

Figure 3.4: Mean monthly solar irradiance and wind speed for the period February 2003 – January 2011 (Raw data source: Elukwatini weather station (26°2'S, 30°47'E), courtesy of the Agricultural Research Council)

The Groenvaly valley is part of the Drakensburg escarpment (see Fig. 3.1), which has strong relief and variable slopes and aspects. Groenvaly is located along a north-west/south-east transect of low mountains and straddles a tributary to the Komati river. The escarpment extends to the lowveld savanna approximately 20km to the east of Groenvaly, and meets the grassland plains of the highveld plateau 40 km to the west.

The soils of the region are mesotrophic red and yellow massive or weak structured soils, (DEAT, 2000a; 2000b). The study area is on a shallow lithic Glenrosa (GS16GS17) and Mispah (Ms10) soil (Fig. 3.7, Fig. 3.8 and Fig. 3.9). Both the Glenrosa and Mispah (GS16GS17) soils have a grey to dark brown topsoil, the difference being in the subsoil. Glenrosa topsoil is located over soil materials mixed with partly weathered rock-derived materials and hard rock fragments while Mispah topsoils are underlain purely by hard rock (ARC, 2004).

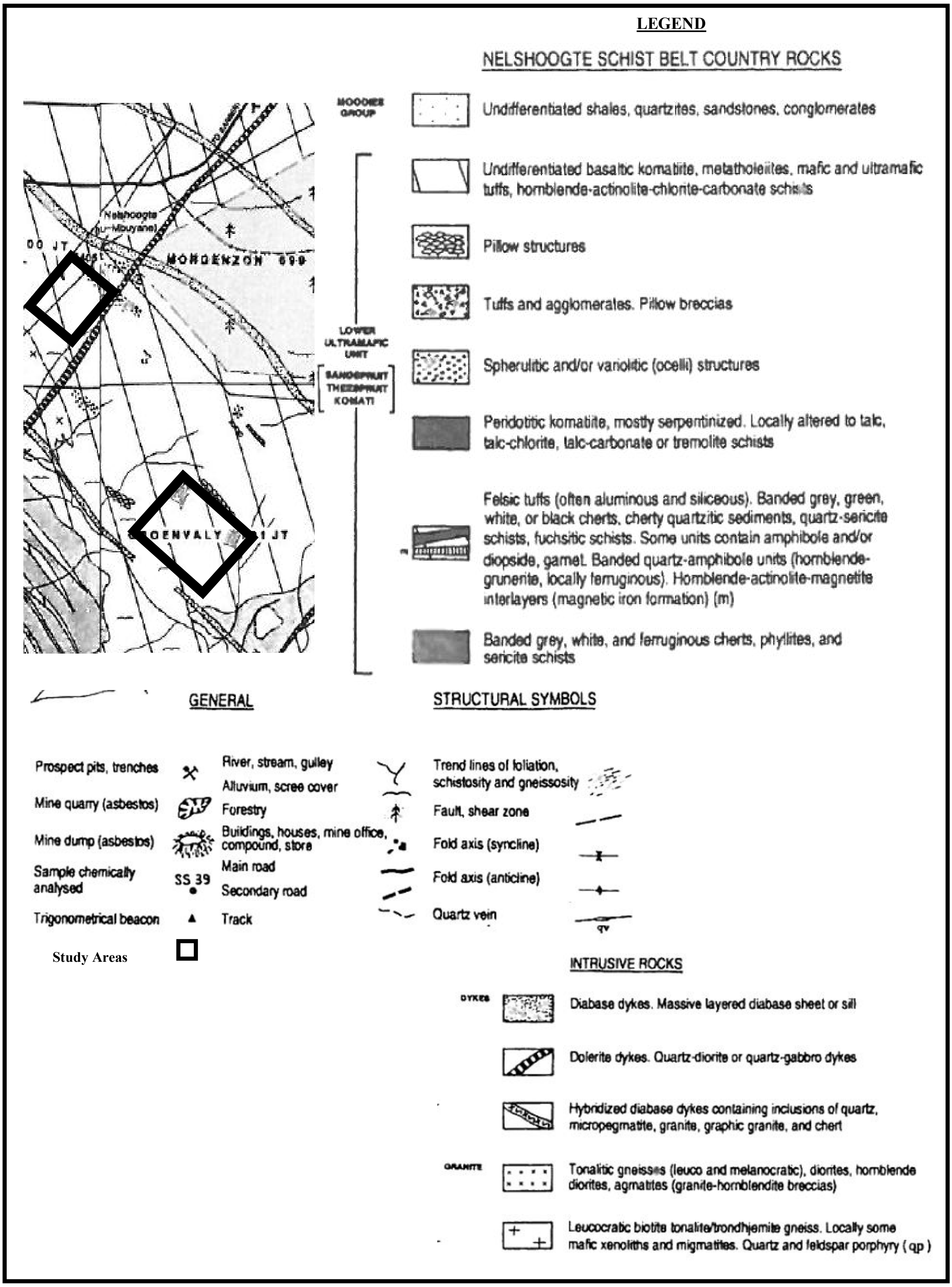

Figure 3.5: Geological map of Groenvaly (modified from Anhaeusser, 2001)

Figure 3.6: Siliceous schist (left) exposed at the northern ridge and basaltic pillow lava exposed on a plantation access road, both at Groenvaly

Figure 3.7: Glenrosa soil (left) and Mispah soil exposed on plantation access roads downslope of the study area

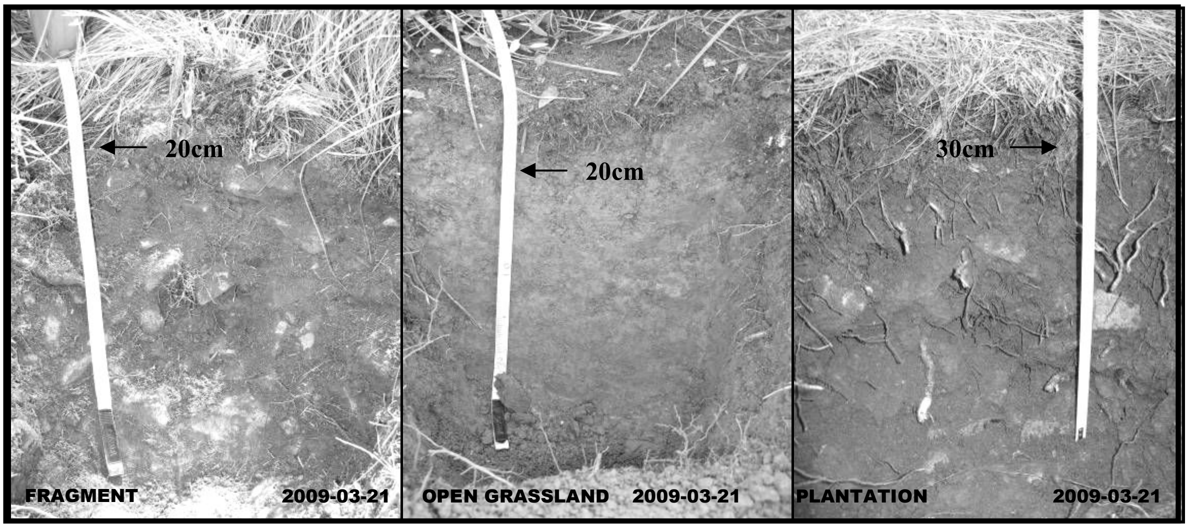

Figure 3.8: Soil profile (from left) in a grassland fragment, in open grassland bordering the plantation and in the plantation

3.3 Vegetation

The vegetation in the region is classified as North-eastern Mountain Grassland, also known as Barberton Montane Grassland (Mucina *et al.*, 2007), and consists of a mosaic of montane forest and grassland. North-eastern Mountain Grassland is restricted to the high altitude of Mpumalanga and, the neighbouring country, Swaziland (Bredenkamp *et al.*, 1999). The grassland is dominated by *Themeda triandra*, *Loudetia simplex* and *Rendlia altera* (van Jaarsveld *et al.*, 1998) and is considered to be a primary grassland that is likely to be older than the associated forest vegetation found in the sheltered ravine (Smit *et al.*, 1997).

In 1994, Groenvaly was planted with a combination of *Pinus elliottii* and *Pinus patula* seedlings at a density of 1750 stems/ha. Prior to afforestation, Groenvaly was used for cattle grazing and it is likely that the grass was burned on a near annual basis (van Jaarsveld *et al.*, 1998).

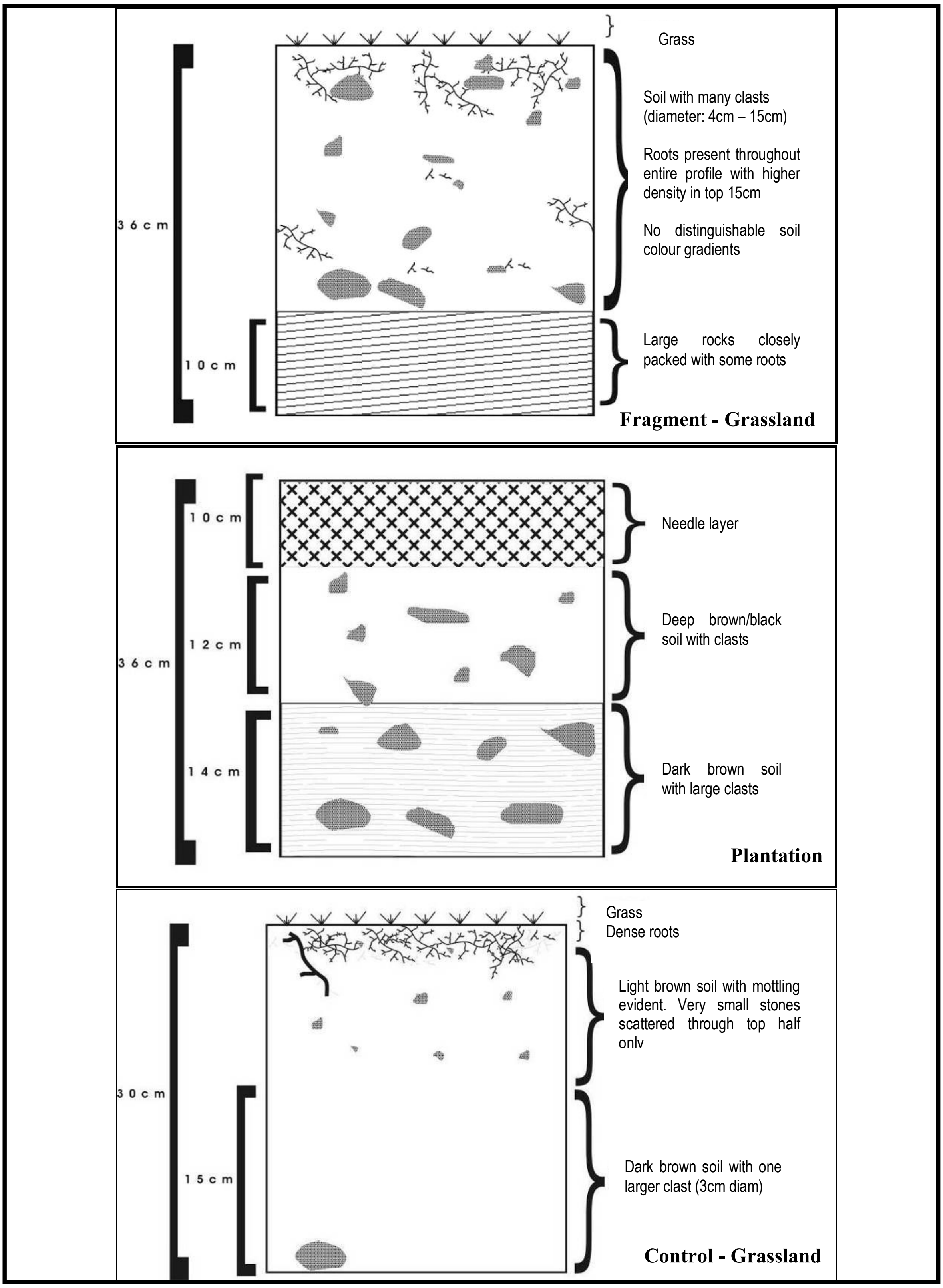

Figure 3.9: Sketch of soil profiles (from top) in grassland fragment, plantation site and grassland control site

3.4 Groenvaly project

The Groenvaly experiment was established in 1994. *Pinus elliotii* and *Pinus patula* were planted around 24 demarcated grassland sites (Fig. 3.10). Twelve of the sites are grassland fragments located inside the plantation; six are 0.25ha in size, and the balance measure 1.5ha. The remaining twelve serve as controls and are located in the neighbouring non-afforested conservation area which is situated on the boundary of the plantation (Fig. 3.10. and Fig. 3.11). All sites are situated on south-westerly aspects at elevations between 1200m and 1600m. Tables 3.1 and 3.2 list the attributes of study sites which are part of the Groenvaly project. Site selection was based on these criteria.

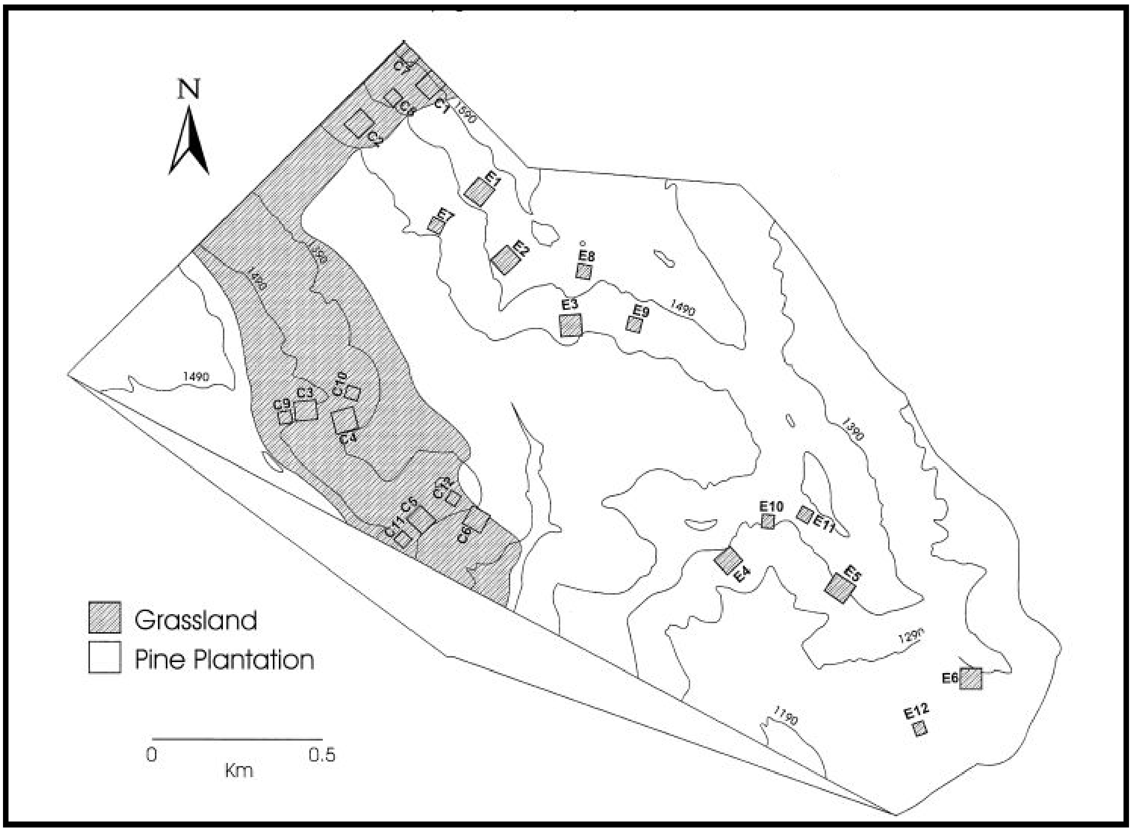

Figure 3.10: Layout of the Groenvaly experimental (E) and control sites (C) (Source: van Jaarsveld *et al.*, 1998)

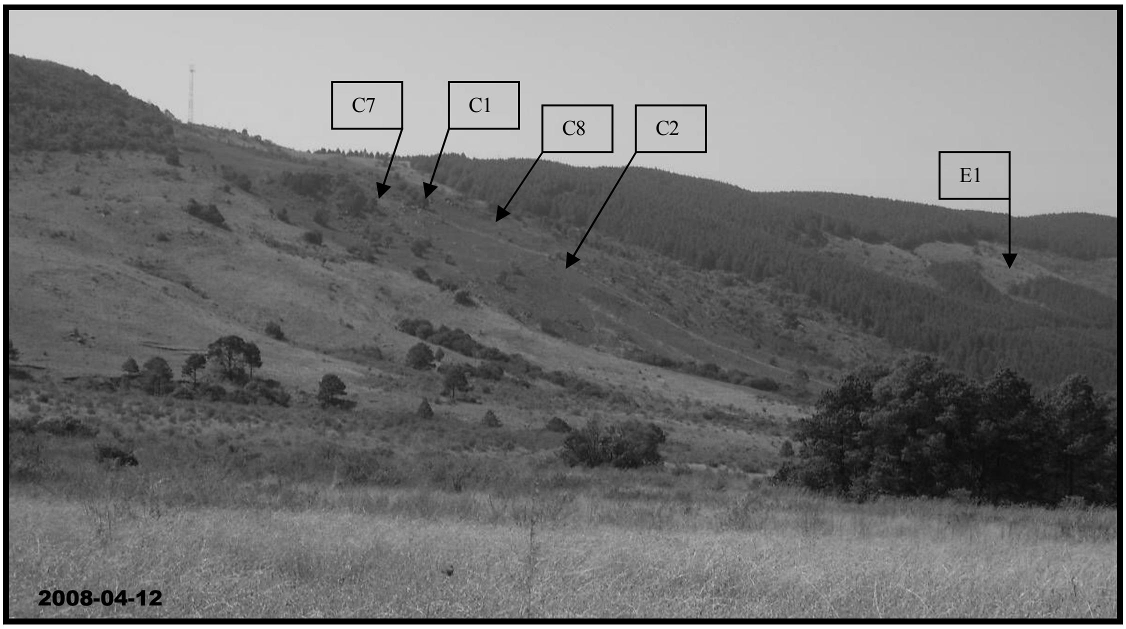

Figure 3.11: Part of the Groenvaly valley, control sites C1, C2, C7 and C8 and experimental site E1 are visible

3.5 Summary

The Groenvaly experiment was originally designed to ensure that experimental and control sites were similar with regards to climatic, geological, pedological, geomorphological and topographical variables. Previous studies have concluded that:

- experimental fragments and control sites were similar in structure and thus could be compared with one another in future studies (Bredenkamp *et al*., 1999)
- there were no measurable reactions by small mammal assemblages to fragmentation (Johnson *et al*., 2002)
- there is an unexpectedly higher degree of endemism for Afromontane Orthoptera than would be expected for a generalist taxon (Foord *et al*., 2002)
- high degrees of botanical endemicity is mirrored in the beetle assemblages (Foord *et al*., 2003).

Table 3.1: Criteria considered for study site selection
Where * = *Helichrysum* sp. cover is larger than grassland cover.

Site	Altitude (masl)	Aspect	Accessibility	Security	Vegetation Cover	Border Composition	Size (ha)
E1	1500	SW	Good	Good	Grassland	Natural bush & plantation	1.5
E2	1495	SW	Good	Fair	Grassland	Plantation	1.5
E3	1440	SW	Good	Fair	*Helichrysum**	Plantation	1.5
E4	1340	SW	Good	Poor	Grassland	Plantation	1.5
E5	1390	SW	Poor	Good	*Helichrysum**	Natural bush & plantation	1.5
E6	1280	SW	Fair	Poor	Grassland	Plantation	1.5
E7	1400	SW	Good	Poor	*Helichrysum**	Plantation	0.25
E8	1515	SW	Good	Good	Grassland	Plantation	0.25
E9	1450	SW	Good	Good	Grassland	Plantation	0.25
E10	1390	S	Good	Poor	Grassland	Plantation	0.25
E11	1440	SW	Good	Poor	Grassland	Natural bush & plantation	0.25
E12	1240	SW	Fair	Poor	Grassland	Plantation	0.25
C1	1590	SW	Good	Fair	Grassland	Grassland & plantation	1.5
C2	1440	SW	Poor	Fair	Grassland	Grassland & plantation	1.5
C3	1490	SW	Fair	Fair	Grassland	Grassland	1.5
C4	1440	SW	Fair	Fair	Grassland	Grassland	1.5
C5	1440	W	Poor	Good	Grassland	Grassland	1.5
C6	1380	W	Poor	Good	Grassland	Grassland	1.5
C7	1590	SW	Good	Poor	Grassland	Grassland	0.25
C8	1500	SW	Fair	Fair	Grassland	Grassland & plantation	0.25
C9	1500	SW	Fair	Fair	Grassland	Grassland	0.25
C10	1440	SW	Fair	Fair	Grassland	Grassland	0.25
C11	1440	W	Poor	Good	Grassland	Grassland	0.25
C12	1440	W	Poor	Good	Grassland	Grassland	0.25

Table 3.2: Summaries of the topographical characteristics of the control and experimental sites at Groenvaly (modified from Van Jaarsveld *et al.*, 1998)

Site	**Characteristic**	**1.5ha fragments (mean ± s.d.)**	**0.25ha fragments (mean ± s.d.)**
Control	Slope (m/m)	0.798 ± 0.13	0.800 ± 0.23
	Altitude (masl)	1448.0 ± 71.2	1486.0 ± 66.5
	Aspect (°)	176.0 ± 30.1	151.0 ± 38.0
Experimental	Slope (m/m)	0.893 ± 0.14	0.799 ± 0.21
	Altitude (masl)	1415.0 ± 96.7	1409.0 ± 45.8
	Aspect (°)	210.0 ± 34.9	190.0 ± 5.5

All the above-mentioned studies were completed during 1994 and 1995, less than two years after establishment of the Groenvaly plantation. For the first time, the impacts of afforestation on microclimate and soil were investigated at Groenvaly. This study was conducted over four years, from 2008 to 2012, when, at the start of the study, the plantation was a more mature age of 14 years. The experimental layout at Groenvaly thus provided a good base for implementing consistent methodology, and meeting the objectives of this investigation about the impact of afforestation on the microclimate and soil of grassland fragments.

CHAPTER 4: METHODS

Study methods were selected according to two main criteria. First, the objectives laid out in Chapter 1, and, second, alignment with the suggested afforestation research focus areas detailed in Chapter 2.

4.1 Site layout

Seven sites were selected for study based on similarity and practicality (Table 3.2 and 4.1); two grassland control sites (C7 and C1), two grassland fragment sites, (E2 and E8) and three pine plantation sites, (P1, P2 and P8). Four sites are part of the existing Groenvaly project (E2, E8, C1 and C7), while the three plantations sites were selected as pairs for the fragments and control sites (Fig. 4.1). All sites are thus located at an altitude between 1495masl and 1590masl, have a south-westerly aspect, are easily accessible from plantation roads and are hidden from direct view from roads and footpaths.

Table 4.1: Attributes of the selected study sites

Site	Altitude (masl)	Aspect	Vegetation Cover	Size (ha)
E2	1495	SW	Grassland	1.5
E8	1515	SW	Grassland	0.25
C1	1590	SW	Grassland	1.5
C7	1590	SW	Grassland	0.25
P1	1582	SW	Pine	1.5
P2	1495	SW	Pine	1.5
P8	1525	SW	Pine	0.25

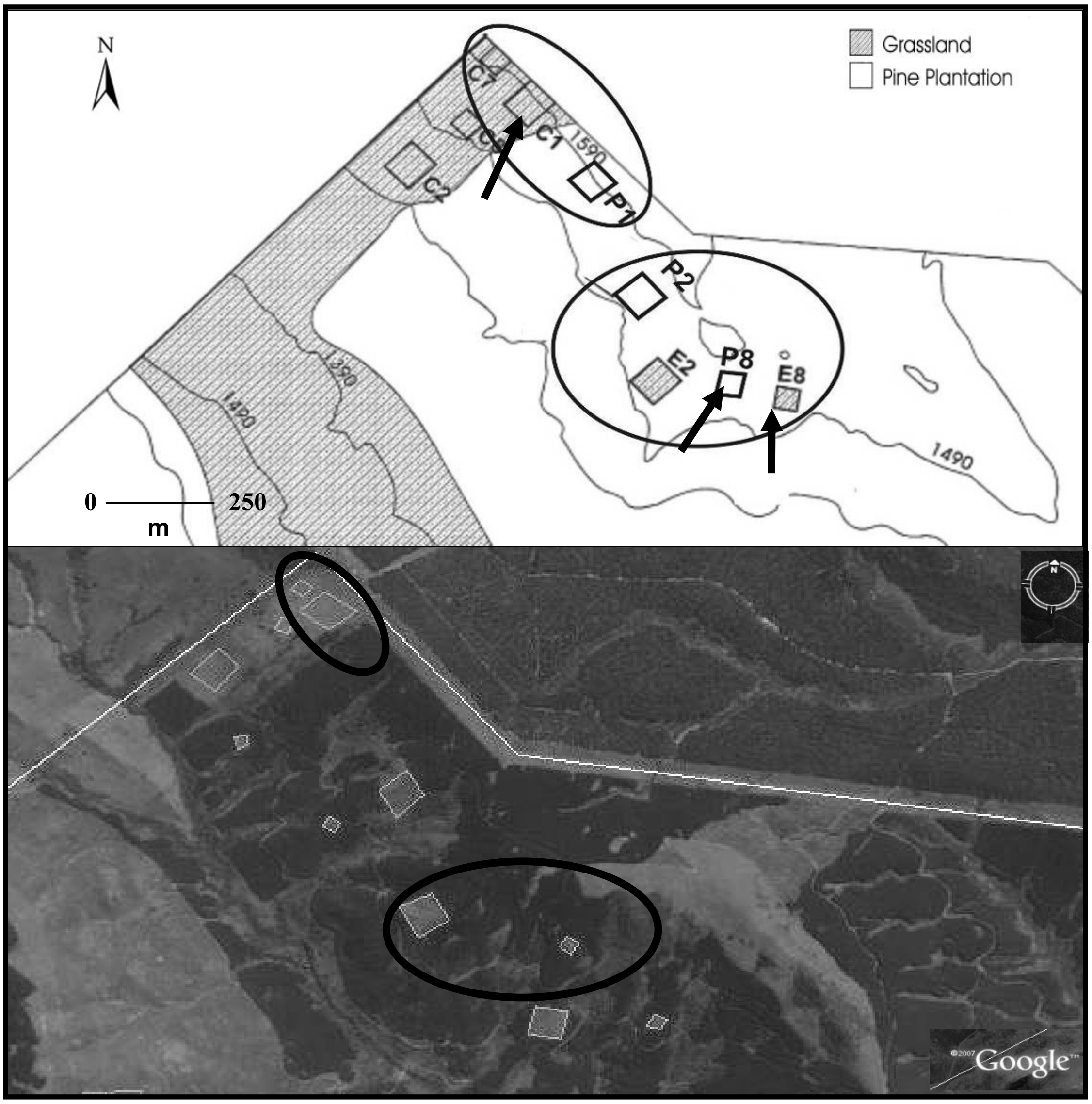

Figure 4.1: Site layout indicating the selected study sites (modified from van Jaarsveld *et al.*, 1998) and the location of Davis weather stations (arrows) and corresponding Google^{TM} image (P = plantation site, E = experimental fragment, C = control site)

E2 and E8 have similar grass cover to the control sites (Brendenkamp *et al.*, 1999) and are entirely surrounded by *Pinus patula*. Dimensions of C1, P1, E2 and P2 are 125m by 125m and the remaining three measure 50m by 50m. Eastern boundaries of P2 and P8 are 150m from the respective western boundaries of E8 and E2. The layout is similar to a few other studies. Singh *et al.*, (2009), Chen *et al.* (2003), Groenendijk *et al.* (2002) and Holl

(1999) all had sites under pine that were paired with adjacent pasture sites. Altitudes of the selected control and experimental sites are higher than the respective means of 1448masl and 1415masl for the group of sites (Table 3.1). C1 and C7 face south-west while the mean for all control sites is a southerly direction (Table 3.1). E2 and E8 are south-west facing and are close to the aspect mean for all experimental sites of 210º (Table 3.1).

4.1.1 Fragments

Extensive work on plant classification has already been undertaken at Groenvaly (Bredenkamp *et al.*, 1999). Fragments are dominated by a very typical species of the Afromontane grassland, *Themeda triandra*, interspersed with *Panicum natalensis* and *Schizachyrium sanguineum* (Bredenkamp *et al.*, 1999). To ensure that fragments and control sites could be compared, burning and clearing of woody vegetation was carried out in March 2009 at the two selected research fragments (E2 and E8). Prior to this exercise no burning or clearing was undertaken and the fragments have never received any fertiliser. Both fragments are entirely surrounded by *Pinus patula* that were planted in 1994 (Fig. 4.2).

Figure 4.2: Fragment site E8 showing three of the four boundaries with the plantation

Both sites E2 and E8 have a south-westerly aspect, an average slope angle of 23.5° and 14.5° and their centre points are 1495masl and 1515masl respectively (Fig. 4.3). Neither of the fragments have uniformly even terrain. There is a small ridge running through the centre of E8 (Fig 4.3) while E2 has a very prominent central ridge and a low gradient, marshy area in the south-western corner.

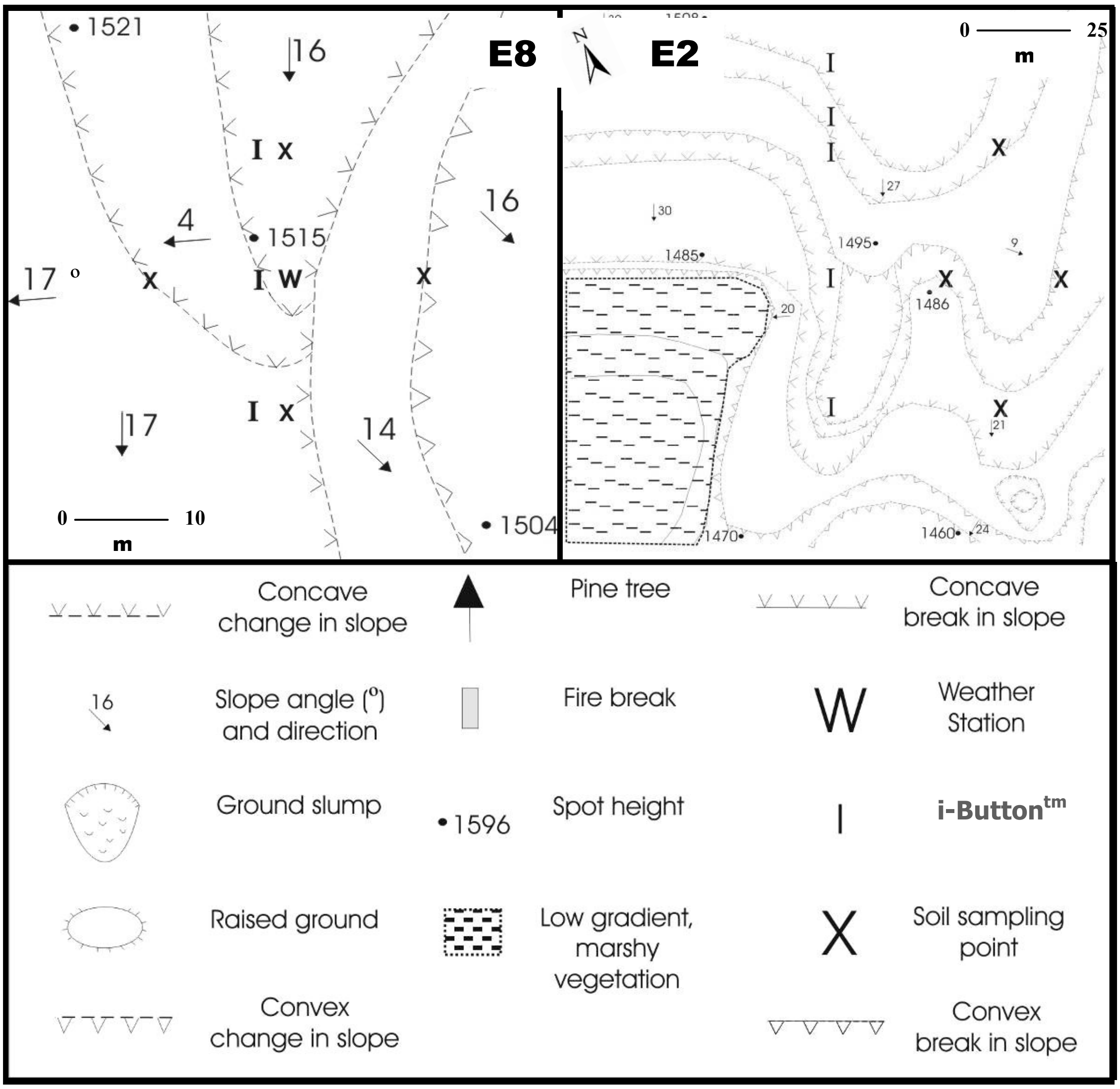

Figure 4.3: Geomorphological maps of E8 (left) and E2

4.1.2 Control sites

Control sites C1 and C7 have the same vegetative composition as E8 and E2 (Bredenkamp *et al.*, 1999) and their centre points are 1582masl and 1596masl respectively. C1 has two ground slumps and is bordered by a bare-soil fire-break and the plantation to the east (Fig. 4.4 and Fig. 4.5). Both sites have a south-westerly aspect and have an average slope angle of 11° (Fig. 4.5). Located directly to the west of C1 is C7, which has fairly uniform terrain with just two areas of raised ground. The sites were burned in July 2010, September 2007 and approximately every second year between 1994 and 2007.

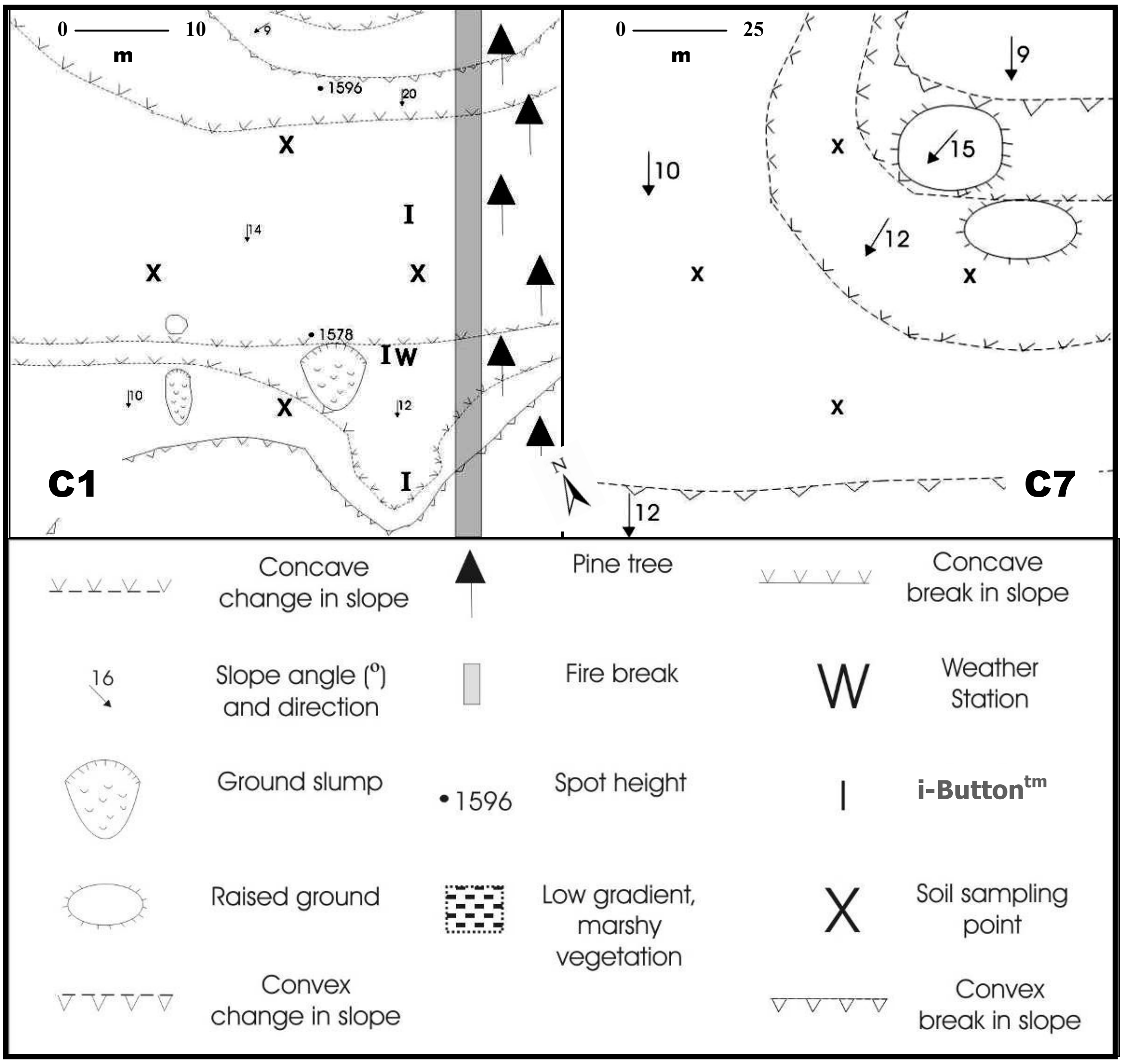

Figure 4.4: Geomorphological maps of C1 (left) and C7

Figure 4.5: Control site C1 looking upslope (left) and downslope

4.1.3 Plantation sites

Aside from the *Pinus patula* trees, plantation sites are devoid of any substantial plant growth (Fig. 4.6). The plantation sites P1, P2 and P8 have a south-westerly aspect, average slope angles of 14°, 23° and 23.5° respectively (Fig. 4.7) and have a mean typical needle depth of 8cm. The sites are situated at an altitude between 1495masl and 1582masl. The dimensions of the plantation sites match those of the grassland and fragment sites to which they are paired; two are 1.5 ha and one is 0.5ha in size.

Figure 4.6: Plantation site P1 (left) and needle depth

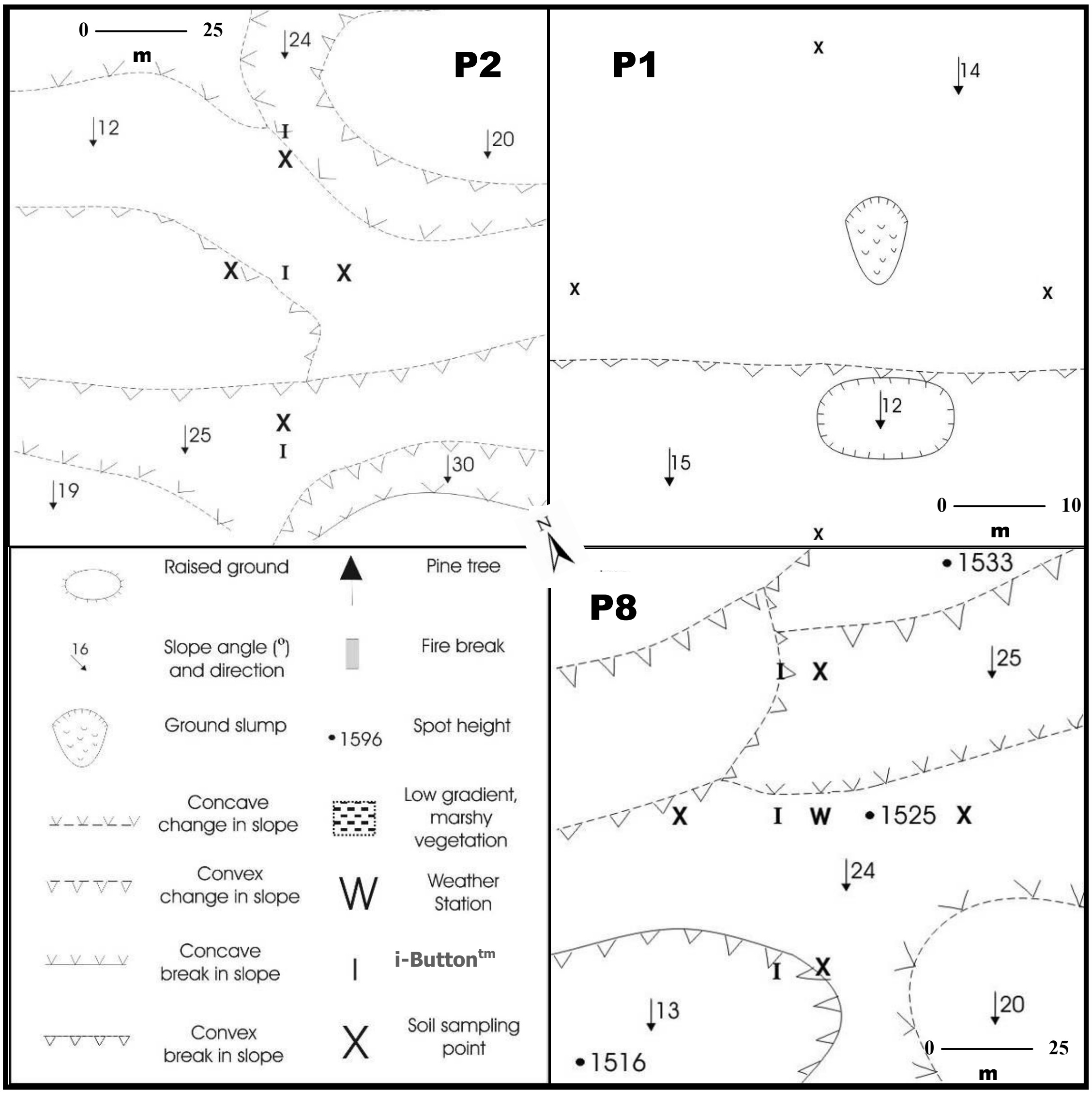

Figure 4.7: Geomorphological maps of (clockwise from top left) P2, P1 and P8

4.2 Objectives

The aim of the study is to investigate the impact that a pine plantation has on the soil properties and microclimate beneath the canopy and in adjacent grassland fragments at both a seasonal and a mean scale. This leads to two objectives (see page 5).

4.2.1 Objective 1 – to compare and evaluate air and soil microclimate and soil chemical properties at a individual, seasonal and mean scale

4.2.1.1 Measurement of air and soil microclimate

The wireless Davis Vantage Pro2 automatic weather station, with the addition of a solar irradiance sensor, was used in this study. The automatic weather stations are complete units that have uses in the agricultural, commercial, recreational and research fields. They have been used in a variety of applications such as in a study of heat stress on cattle (Eigenberg *et al.*, 2005, 2007), for rice field monitoring (Kobayasi *et al.*, 2010), for interior vehicle temperature monitoring (McLaren *et al.*, 2005) and in an analysis of a self-diagnostic algorithm (Li *et al.*, 2007).

The Davis Vantage Pro2, in particular, has been independently proven to perform well against both the American standard synoptic measurements and the stricter British instrumentation standards (Burt, 2009). In Burt's (2009) evaluation of the wireless Davis Vantage Pro2 performance, the system excelled at air temperature and barometric pressure measurements and performed adequately in humidity, wind speed and wind direction monitoring. The only shortcoming noted was the poor accuracy of the rain guage, which appears to be due to an "*an inherent but random variation in the unit's performance*" (Burt, 2009:10). Total rainfall at each of the study sites in this particular Groenvaly study is of a lower priority, due to the canopy effect, compared to the other microclimate parameters and is compensated for by soil moisture analysis.

Three wireless Davis Vantage Pro2 automatic weather stations were set up in C1, P8 and E8 (Fig. 4.1 and Fig. 4.8) in March 2009. The station at C1 served as a control for the study while plantation and fragment microclimate parameters were measured by the stations at P8 and E8 respectively. Camouflage, in the form of hessian cloth, was required to help protect the C1 station from visibility and theft, and it was arranged in such a way that its sensors were not affected. Sensor height, resolution and accuracy are presented in Table 4.2. For the period March to September 2009 mean values were stored at two-hourly intervals, following which, from October 2009 to March 2011, data were stored at hourly intervals.

Figure 4.8: Three Davis Weather stations in (from left) E8, P8 and C1

Table 4.2: Height above ground, resolution and accuracy of air microclimate sensors

Sensor	**Height (above ground)**	**Resolution**	**Accuracy**
Air Temperature	0.9m	0.1°C	0.5 °C
Humidity	0.9m	1%	3%
Wind Speed	1.8m	0.1m/s	1m/s
Wind Direction	1.8m	1°	7°

Vapour pressure deficit was calculated as follows:

Vapour pressure deficit = saturated vapour pressure – air vapour pressure

where:

air vapour pressure = saturated vapour pressure x relative humidity

and

$$\text{saturated vapour pressure} = e^{A/T + B + CT + DT^2 + ET^3 + F\ln T} \text{ kPa}$$

where:

A = -1.88E4 E = 1.69E-11

B = -13.1 F = 6.456

C = 1.5E-2 T = Temperature (°C) + 273.15

D = 8E-7

iButtons™ are small, convenient, self-sufficient and inexpensive devices that measure and store both temperature and humidity. They have been used in ecological, physiological, hydrogeological, meteorological and geographical studies (*e.g.* Mzilikazi, *et al.*, 2002, Johnson *et al.*, 2005, Dumas *et al.*, 2007, Devine and Harrington, 2007, Gehrig-Fasel *et al.*, 2008). A total of 34 Higrochron™ iButtons™ were available, these were installed at five of the seven sites (E8, P8, E2, P2 and C1) to give representation across the different fragment sizes, plantation sites and control sites. Installation points for the iButtons™ were located equidistant to one another along the centre line of each of the five study sites and were installed at 2cm and 10cm below the soil surface (Fig. 4.9). Each iButton™ was affixed to a plastic key tag to aid retrieval. An additional four iButtons™ were installed in E2 at 25m and 13m from the top boundary of the fragment in order to be in similar locations to those in E8 which were also located 25m and 13m from the fragment boundary. From October 2009 to December March 2011, data were stored at hourly intervals. The resolution and accuracy of the iButtons™ are presented in Table 4.3.

Table 4.3: Depth below ground, resolution and accuracy of iButton™ sensors

Sensor	**Depth (below ground)**	**Resolution**	**Accuracy**
iButton™ digital thermometer	2cm and 10cm	0.0625°C	0.5 °C

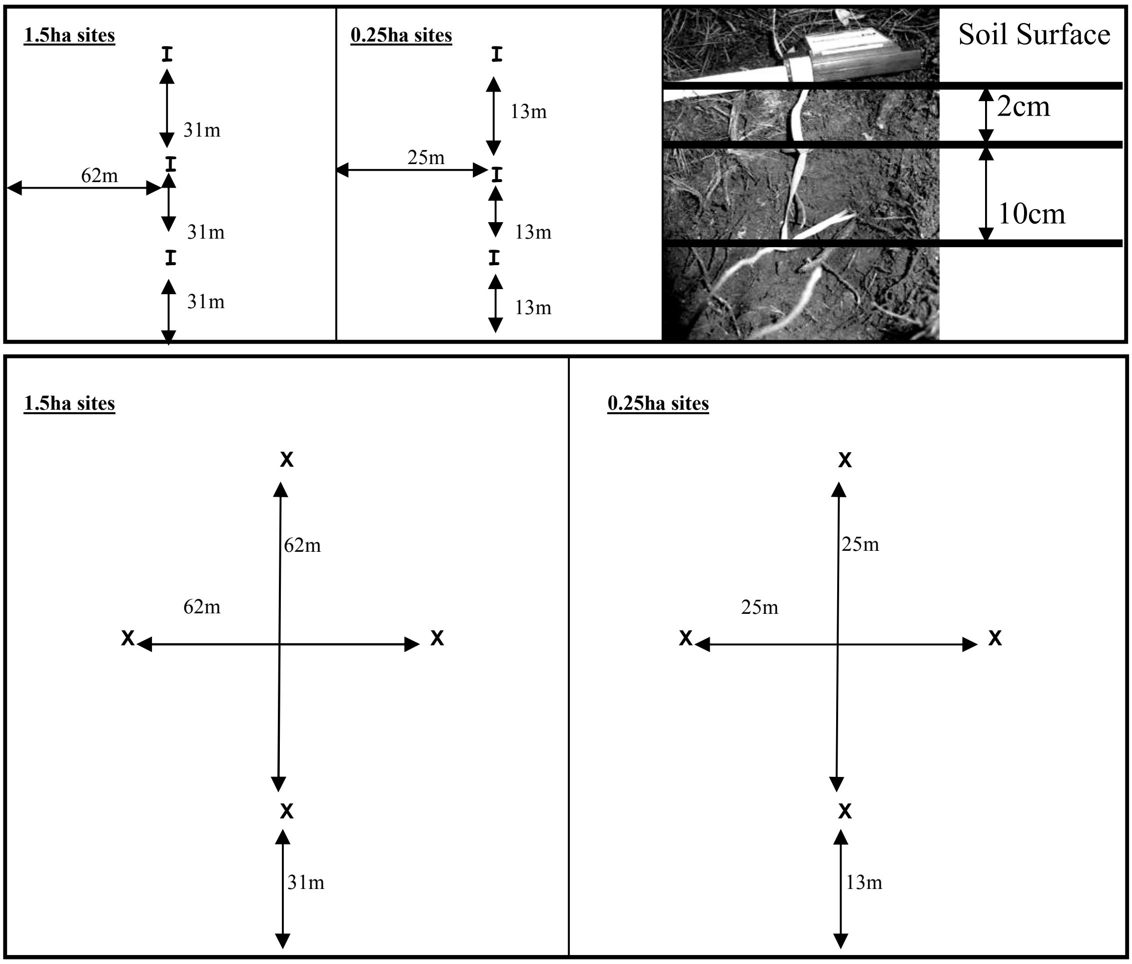

Figure 4.9: Plan view layout of iButton™ locations in 1ha sites (top left) and 0.25ha sites (top middle), iButtons™ inserted in the soil profile (top right). I = iButton™ location. Plan view layout of soil sample locations in 1ha sites (bottom left) and 0.25ha sites (bottom right). X = soil sample location

Soil sampling was conducted in all seven study sites in September 2008, March 2009, December 2009 and July 2010 and represents four seasons. Soil samples were taken at a depth of 0–10cm using a soil corer (10cm in diameter) at 4 equidistant locations at each site (Fig. 4.9). Exceptions were P2 and E2. Local topography necessitated modifying the selection method of soil sample locations in E2 (Fig. 4.3). The soil sample locations at P2 were similarly modified to match the layout in E2 (Fig. 4.7). Soil moisture content was determined by the author using the gravimetric method. Because soil moisture is of particular interest, the soil samples taken in September 2010, December 2010 and March 2011 were solely for moisture analysis data over the early, mid and late summer periods.

4.2.1.2 Measurement of soil chemical properties

In many studies, chemical analyses have been performed on soil samples taken during one sampling event and thus seasonal trends have been ignored. Exceptions are Hart *et al.* (1993), Parfitt *et al.* (1997), Chen *et al.*, (2003), Smith and Johnson (2004), Cao *et al.* (2007), Zhao *et al.* (2009) and Smith and Johnson (2004). In this Groenvaly study, soil samples were collected during each of the four seasons. All the samples underwent the same comprehensive analysis (Table 4.4) and each sample was analysed separately; a method that differs from many other studies where soil samples from one plot are combined to from one bulk sample (Alfredsson *et al.*, 1998; Holl, 1999, Chen *et al.*, 2000, 2003; Zhao *et al.*, 2009). All soil analyses, except for the moisture content, were conducted by the Chemtech Soil Laboratory in Sasolburg. Samples were dried overnight at 50°C, crushed and passed through a 2mm sieve before undergoing any analysis. The methods used were the standard methods from the Agri Laboratory Association of South Africa AgriLASA Soil Handbook (2004). Most of the test methods are common with other studies such as the Walkley-Black method for testing organic carbon (Holl, 1999; Zhao *et al.*, 2007; Hu *et al.*, 2008; Zhao *et al.*, 2009) and the pH(KCl) method of testing pH (Lilienfein *et al.*, 2000). The only method which was not used in other studies was the Bray–1 test for inorganic phosphorous. A discussion on the different phosphorous methods and their applications is found in Chapters 2 and 6.

Table 4.4: Soil tests, method used and reference to the same method used in other published research on the impact of afforestation on soil

Variable	**Method**	**Method reference**
Sand, silt and clay fraction	Pipette Method. Wet sieving of Calgon-dispersed sample.	McKinley *et al.*, 2008
pH	pH (KCl): 1N potassium chloride, left to stand for 60 minutes.	Lilienfein *et al.*, 2000
Phosphorus	Bray 1 – ammonium fluoride and hydrochloric acid extracted solution, read on Inductive Coupled Plasma Optical Emission Spectrometry.	None
Potassium, Calcium, Magnesium, Sodium, Manganese	Ambic 1 – Ammonium-acetate extracted solution, read on Inductive Coupled Plasma Optical Emission Spectrometry.	Jobbágy and Jackson, 2003
Organic Carbon	Walkley-Black method.	Holl, 1999; Zhao *et al.*, 2007; Hu *et al.*, 2008; Zhao *et al.*, 2009
Extractable Inorganic Nitrogen (Ammonium Nitrogen and Nitrate Nitrogen)	Potassium sulphate extraction followed by automated colorimetric analysis.	Ndala *et al.*, 2006
Soil moisture	Gravimetric method. Undisturbed samples were oven dried at 105ºC until a constant mass was reached.	Holl, 1999; Farley *et al.*, 2004; Zhao *et al.*, 2007; Macdonald *et al.*, 2009; Singh *et al.*, 2009; Zhao *et al.*, 2009

4.2.1.3 Comparison of within-site, between-site, seasonal and mean data

R: A Language and Environment for Statistical Computing (R Development Core Team, 2010) was used for all statistical analysis and all graphical illustrations.

4.2.1.3.1 Soil temperature, wind speed, humidity, air temperature, solar irradiance

Daily means, daily maximums and daily minimums were extracted from the data. Means of the daily means, daily maximums and daily minimums as well as the standard errors were calculated for each category of site (fragment, plantation or control) for each season. A column was inserted alongside all air and soil microclimate data. This column contained the number of days elapsed since the first day on which data collection began (1st April 2009). The "lme" function, in the non-linear mixed effects model (nlme) package, was used to run a mixed model effects ANOVA of the number of days elapsed against the data points together with the corAR(1) function to remove the temporal autocorrelation. The raw residuals and normalised residuals were plotted to verify the effectiveness of the corAR(1) function on each dataset. The corAR(1) function was effective in removing the temporal autocorrelation from all datasets. A generalised least squares linear model (glm) of the data points was generated against the site type with the corAR(1) function, and an ANOVA was run on the model. This ANOVA was performed on the seasonal means of the daily means, daily maximums and daily minimums as well as the overall mean.

4.2.1.3.2 Soil nitrogen, organic carbon, phosphorous, potassium, magnesium, calcium, sodium, moisture, pH

Means were calculated for each category of site and for each season. An ANOVA was run on a linear model (lm) of the data points against site type. This ANOVA was performed on the seasonal means as well as the overall mean.

4.2.2 Objective 2 – Possible mechanisms responsible for observed differences

4.2.2.1 Boundary effects

Shading was determined by measuring tree heights at three points within each fragment. An optical clinometer was used to measure the angle from the base of a tree to its tip. This angle, together with the distance from the measurement point to the base, was used to calculate the tree height in metres. The mean slope angle (degrees) from the measurement point to the tree base was used together with mean tree height (metres) and latitude (decimal degrees) to calculate shadow length at the equinoxes and June solstice in E2 and E8. The equations are shown below.

June solstice shadow length =

(Tree height x SIN (latitude+23.40639))/SIN(90 – (latitude + 23.40639) – slope angle)

Equinox shadow length =

(Tree height x SIN (latitude))/SIN(90 – latitude – slope angle)

Spatial distribution of pine needles blown into fragments from adjacent pine trees was determined by physical sampling. Pine needles were collected from 15 sample points in E2, and 12 sample points in E8 (Fig. 4.10). A 1m by 1m square was placed at each sample point (Fig. 4.11) and all visible plant litter was collected. Pine needles were later separated from the plant litter, dried and then weighed.

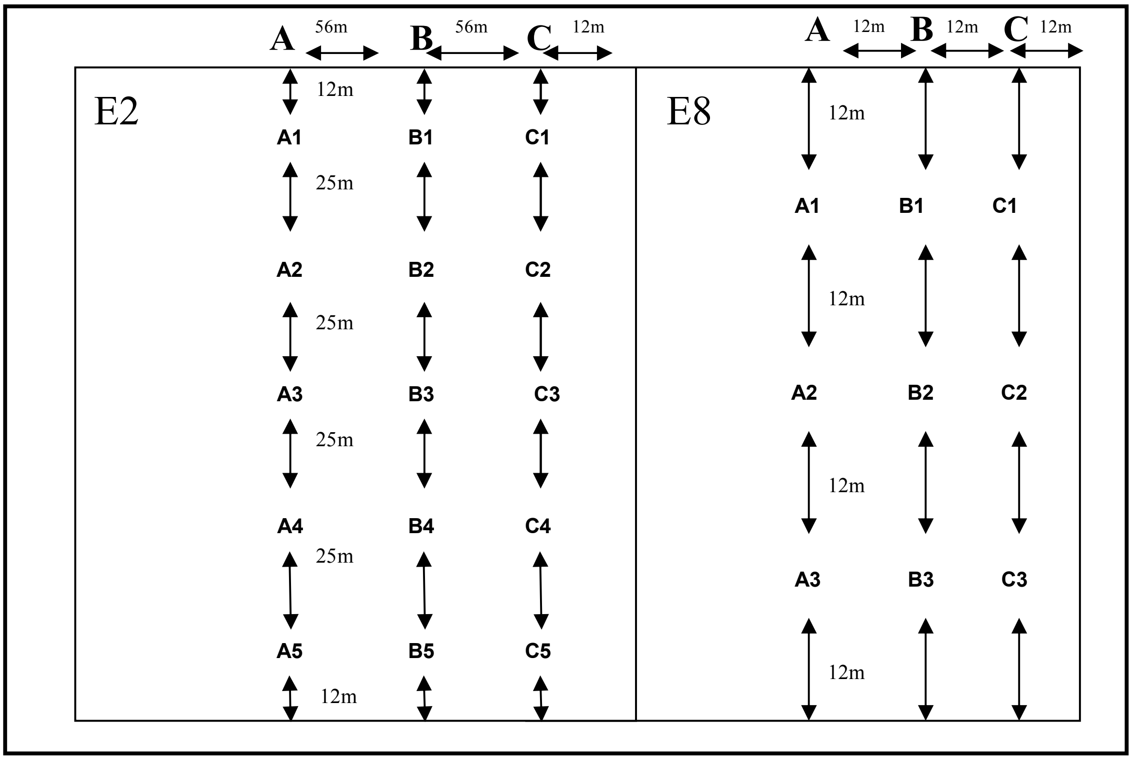

Figure 4.10: Plan view layout of pine needle sample locations for E2 (left) and E8. Arrows indicate distances between sampling points.

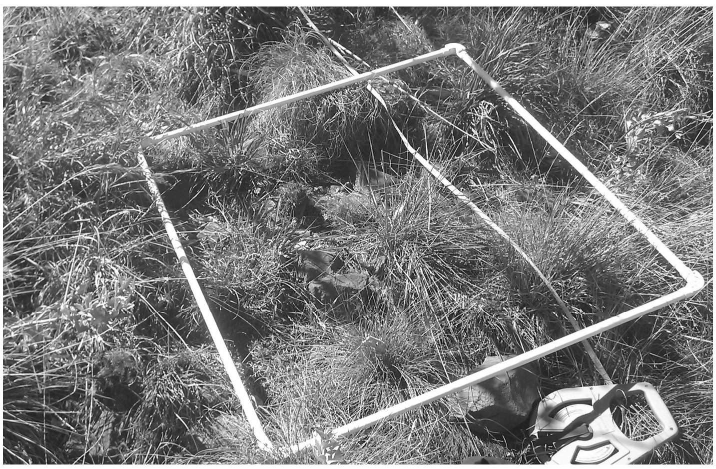

Figure 4.11: 1m by 1m grid used to collect plant litter

4.3 Dataset

The dataset that was obtained is summarised in Table 4.5. The Davis stations had technical failures in November 2009, May and June 2010. Total data collected from the weather stations represent 24 months at P8 and C1 and 23 months at E8. The iButtons™ had technical failures in April and February 2010. Eighteen months of soil temperature data were collected. These data provide the basis for the results presented in the following chapter.

Table 4.5: Dataset for the Davis AWS, iButtons™, chemical soil analysis and soil moisture analysis. A shaded cell represents a successful collection

	2008	2009										2010												2011			
	Sep	Mar	A	M	J	J	A	S	O	N	D	Jan	F	M	A	M	J	J	A	S	O	N	D	Jan	F	M	Total
Davis AWS (Grassland Fragment E8)		■	■	■	■	■	■	■	■	■	■	■	■	■	■			■	■	■	■	■	■	■	■	■	23 months
Davis AWS (Plantation P8)		■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	24 months
Davis AWS (Grassland Control C1)		■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	24 months
iButtons™ (E2, E8, P2, P8, C1)								■	■	■	■	■			■	■	■	■	■	■	■	■	■	■	■	■	17 months
Chemical soil analysis (E2, E8, P2, P1, P8, C1, C2)	■	■									■							■									4 seasons
Soil moisture analysis (E2, E8, P2, P1, P8, C1, C2)	■	■									■							■		■			■			■	7 seasons

CHAPTER 5: RESULTS

Data were analysed at the within-site, between-site, seasonal and mean scale. The within-site and between-site data are presented first, followed by a detailed comparison of each season and sampling date. The mean results follow the season results. Results for boundary effects make up the final section of the chapter. Significant within-site differences indicate differences between grouped values of each of the four specific sampling points within a specific grassland fragment for a certain parameter. Significant between-site differences indicate differences between grouped values for E2 and grouped values for E8 for a specific parameter. Where seasonal results are presented, significant between-site differences indicate differences between grouped values of the three site types (control sites, fragments and plantation sites) for a specific parameter only within that particular season. Where mean results are presented, significant between-site differences indicate differences between grouped values of the three site types for a specific parameter.

5.1 Within-site and between-site results

Potassium and Calcium were the only parameters that exhibited within-site differences in Fragment E8 and E2 respectively (Fig. 5.1, Fig. 5.2 and Appendix Fig. A.1, Fig. A.2, Fig. A.3, Fig. A.4, Fig. A.5, Fig. A.6). All remaining groups of results for each sampling point over the four sampling dates were not significantly different.

Extractable N, nitrate, SOC and soil moisture values were significantly different between fragment E8 and fragment E2 (Table 5.1).

Table 5.1: Means across all seasons for extractable N, nitrate, ammonium, pH, P, Organic C, K, Ca, Mg, Na, and soil moisture in grassland fragments E8 and E2, Df = 1, asterisks indicate significant between-site differences for grassland fragments (**p<0.001, ***p<0.0001)

	Fragment E8	**Fragment E2**	**F value**
Extractable N (ppm)	55	25	19.034***
Nitrate (ppm	39	9	36.076***
Ammonium (ppm)	15	16	0.005
pH	4.5	4.5	0.003
P (ppm)	4	3	1.557
Organic C (%)	5.3	3.6	5.037*
K (ppm)	106	101	0.114
Ca (ppm)	1384	1190	1.823
Mg (ppm)	657	715	0.366
Na (ppm)	16	17	0.030
Soil Moisture	0.38	0.26	10.815**

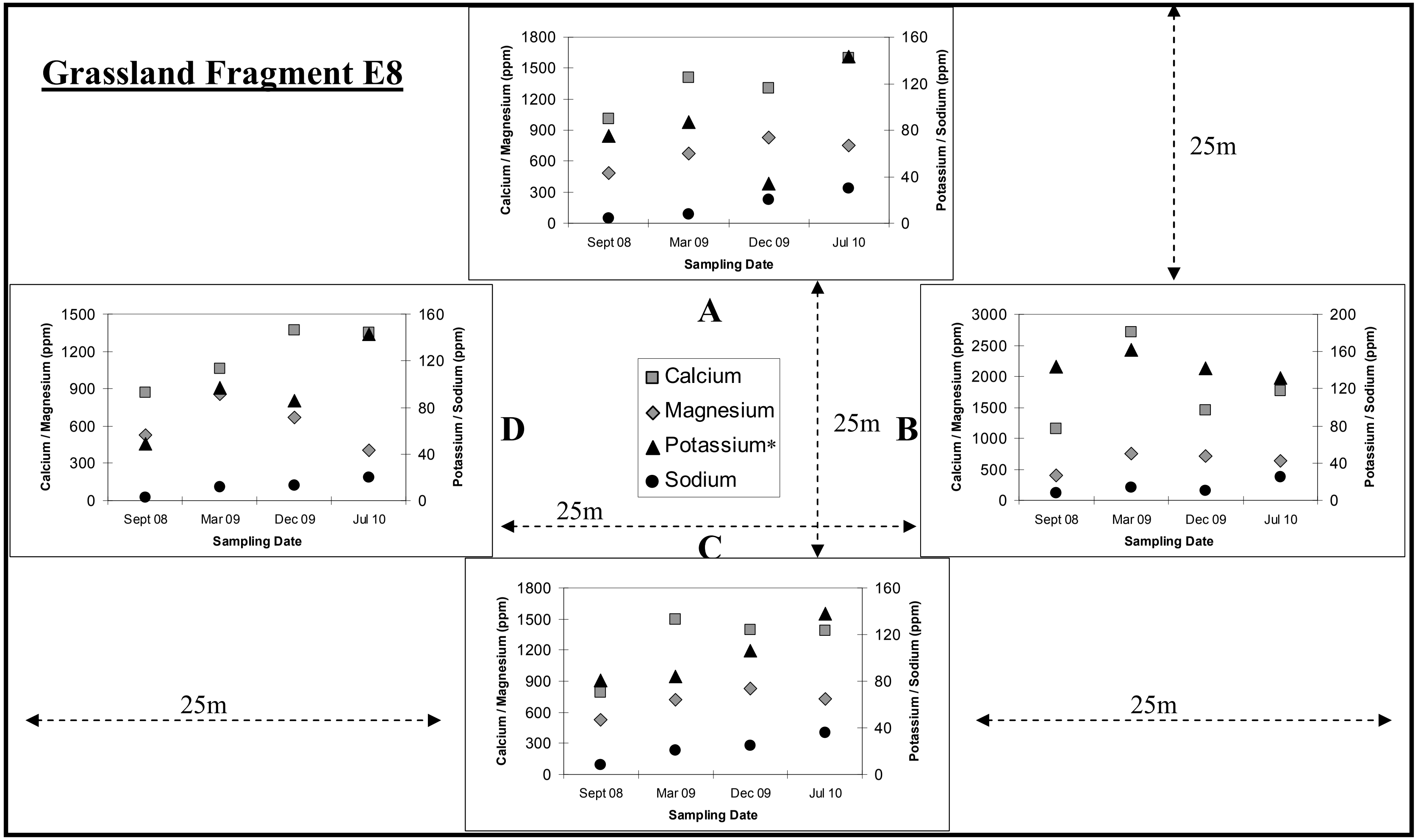

Fig 5.1 Calcium, Magnesium, Potassium and Sodium results for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10) in grassland fragment E8. Distances of sampling points from fragment edges and from each other are indicated. (Df = 3, * indicates a significant within-site difference, p<0.1)

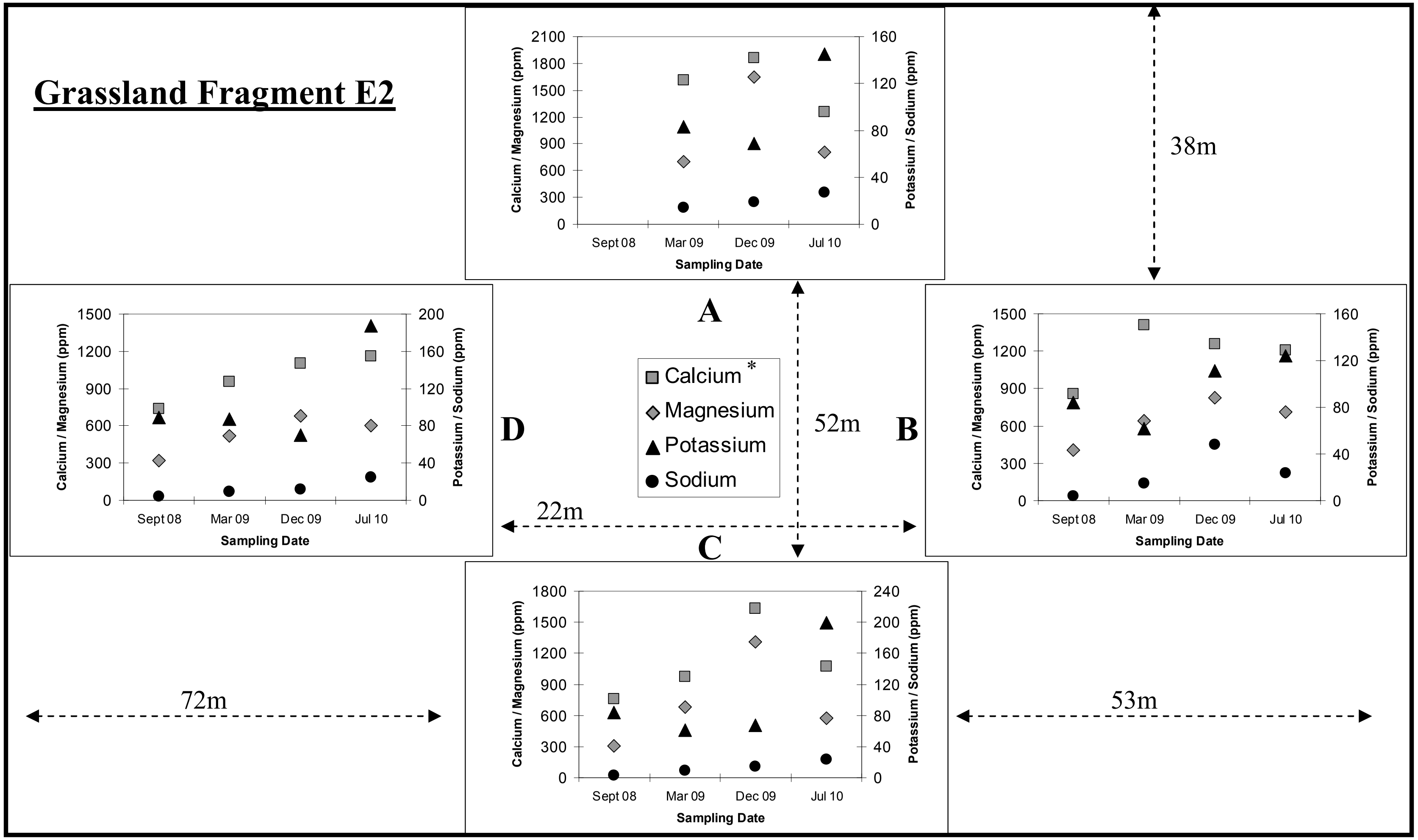

Fig 5.2 Calcium, Magnesium, Potassium and Sodium results for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10) in grassland fragment E2. The sample for point A in September 2008 was misplaced whilst in transit to the Laboratory. Distances of sampling points from fragment edges and from each other are indicated. (Df = 3, * indicates a significant within-site difference, p<0.1)

5.2 Seasonal results

5.2.1 Nitrogen

The highest extractable nitrogen (N) concentration for each site occurred in autumn. There is a decrease in N over winter, with the lowest concentration across all sites occurring in spring (Fig. 5.3). Control sites consistently had the lowest N except for spring where it was the same as the plantation sites. Plantation sites had lower N concentrations than the fragments in spring and winter but had higher N in summer and autumn. Significant between-site differences of N were found across all four seasons (Fig. 5.3). Nitrate concentrations were lowest in the control sites in all seasons (Fig. 5.3); plantation sites had the highest nitrate levels in autumn, while the fragments had the highest levels in spring and winter. Ammonium concentrations were similar in all sites across all seasons (Fig. 5.3); the only significant difference was in spring.

5.2.2 Soil Organic Carbon

Soil organic carbon (SOC) at Groenvaly varied between 2% and 7% when measured over the two years. The highest and lowest SOC measurements were in the fragments in winter and summer respectively. Summer was the only season where significant between-site differences were found (Fig. 5.4). In autumn, SOC was lowest in the plantation sites; however, all the sites were very similar. SOC was at its highest for all sites in winter.

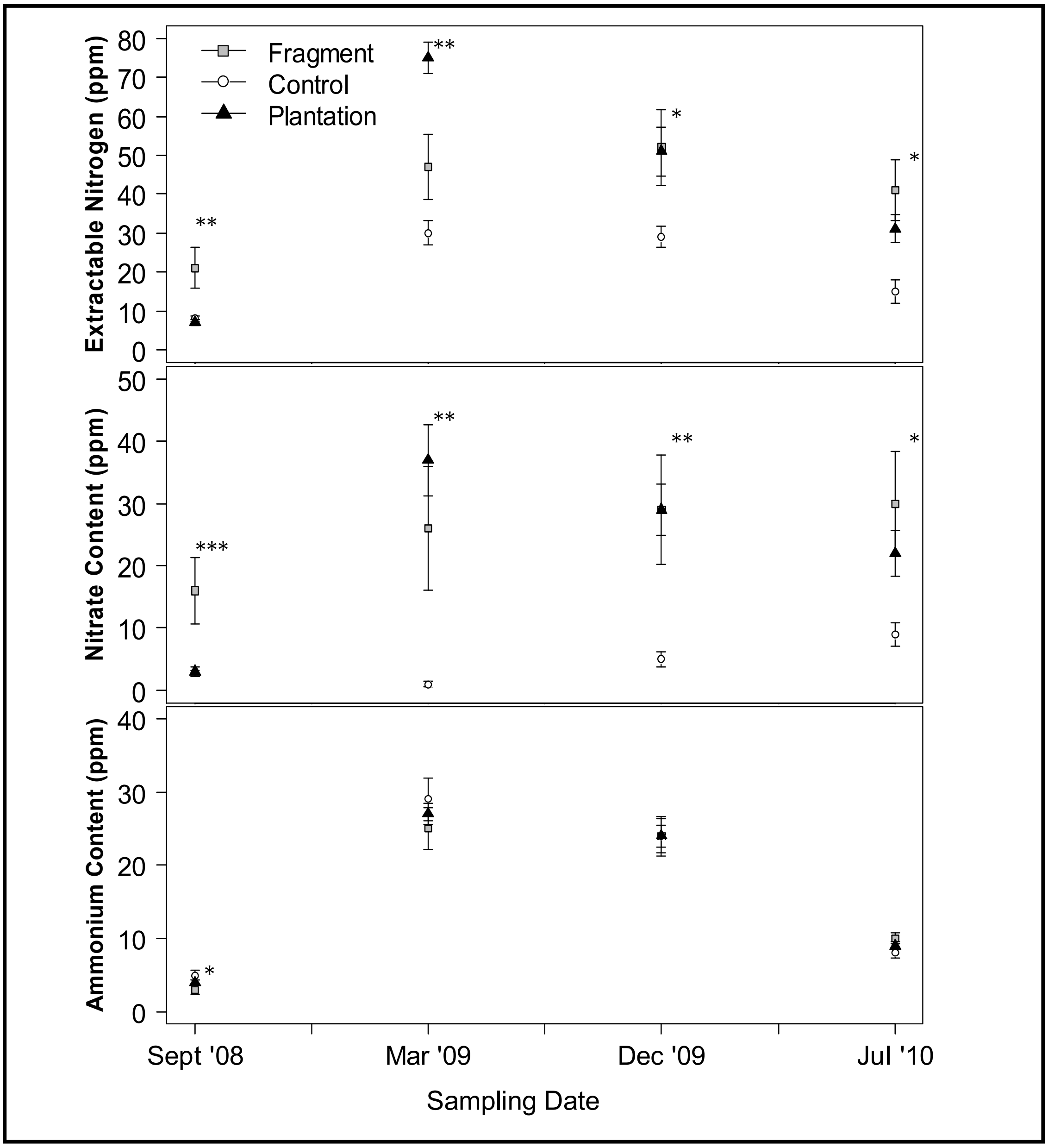

Figure 5.3: Mean total extractable N, nitrate and ammonium content for September (spring), March (autumn), December (summer) and July (winter), asterisk indicates significant between-site differences (* = p <0.01, **=p<0.001, ***=p<0.0001)

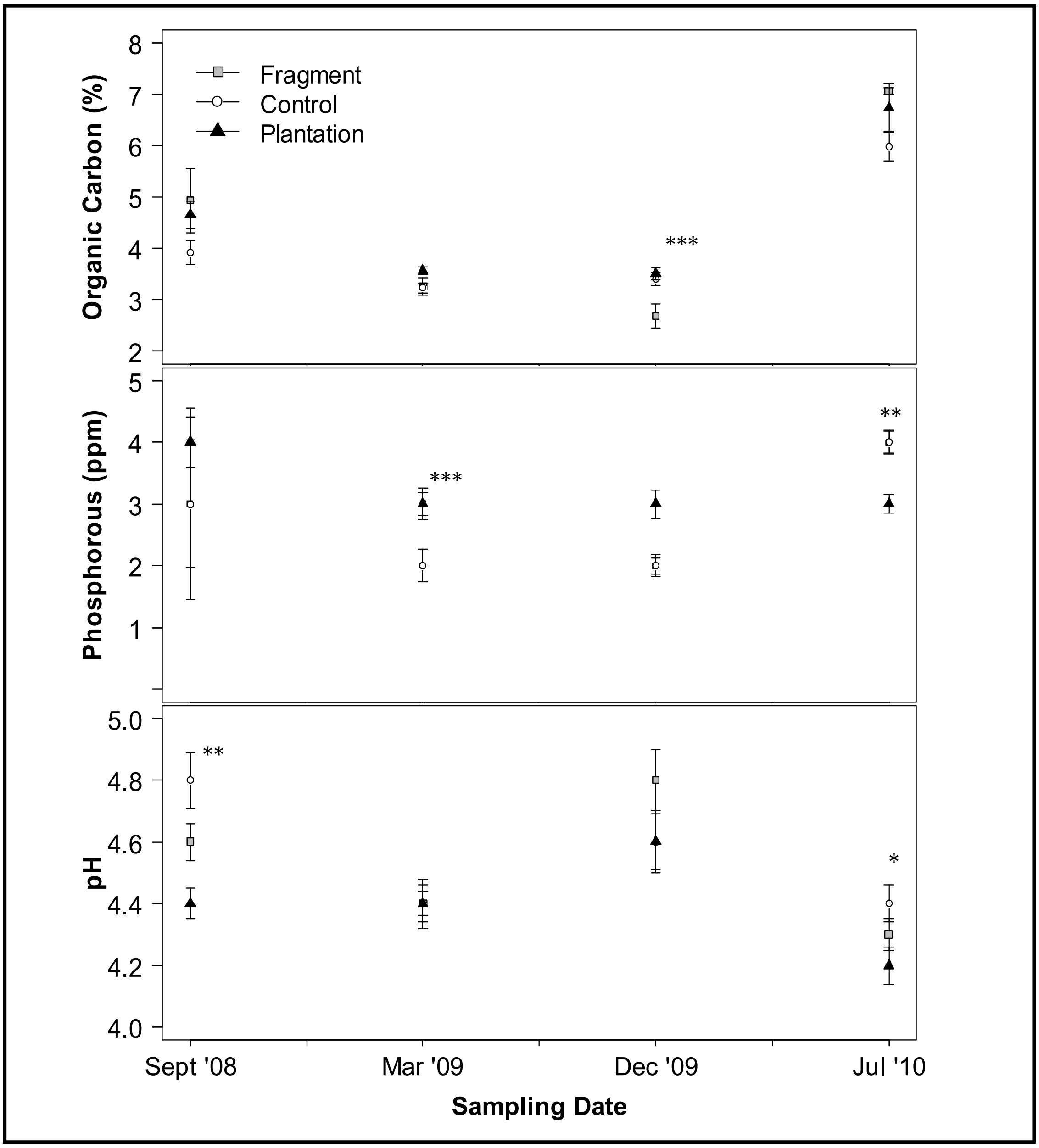

Figure 5.4: Mean organic carbon, phosphorous and pH for September (spring), March (autumn), December (summer) and July (winter), asterisk indicates significant between-site differences (* = p <0.01, **=p<0.001, ***=p<0.0001)

5.2.3 Phosphorous

Concentrations of phosphorous (P) were highest in the plantation in all seasons except winter (Fig. 5.4). The control sites were the lowest in autumn and the highest in winter and there were significant differences between sites in these seasons. P was significantly lower in the control sites in autumn and significantly lower in the plantation sites in winter. Values in the fragments only differed from the control in autumn 2009.

5.2.4 pH

The plantation sites had the lowest pH in all seasons and the biggest differences were in spring and winter where the plantation was respectively 0.4 and 0.2 pH units lower than the control (Fig. 5.4). These seasons had significant between-sites differences. In autumn, the mean pH was the same for all sites while mean pH in the fragments was lower than the control sites in spring and winter, higher in summer and the same in autumn. Variation of pH was within a range of 4.2 to 4.8 over the four seasons.

5.2.5 Major cations – potassium, calcium, magnesium, sodium

Potassium (K) concentrations were highest in the control sites and lowest in the plantation sites in all seasons (Fig. 5.5). Significant differences between sites were found in autumn and winter.

Calcium concentrations were highest in the plantation sites and lowest in the control sites in all seasons (Fig. 5.5). There were significant differences between sites only in summer.

Magnesium concentrations were highest in the fragments and lowest in the control sites in all seasons (Fig. 5.5). Significant differences between sites are evident in all seasons.

Sodium concentrations were highest in the plantation sites in all seasons except winter (Fig. 5.5). A steadily increasing trend across all sites is apparent over the sampling period.

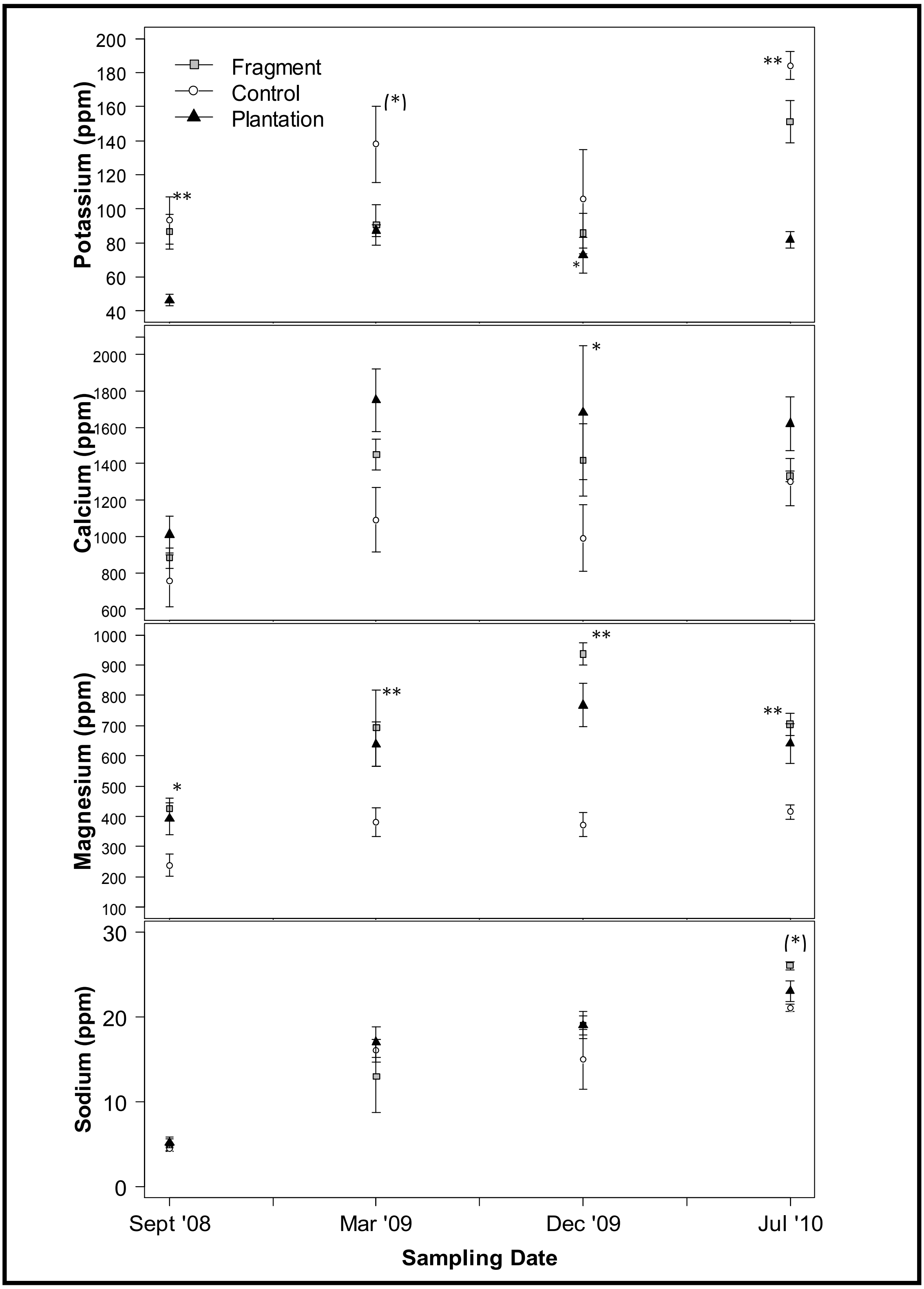

Figure 5.5: Mean K, Ca, Mg, Na for sampling dates in September (spring), March (autumn), December (summer) and July (winter), asterisk indicates significant between-site differences ((*) = p <0.05, * = p<0.01, ** = p<0.001, *** = p<0.0001)

5.2.6 Air temperature

The mean temperature in the fragment was slightly higher than the control and plantation in all seasons (Fig. 5.6). Mean air temperatures in the control and plantation were similar in all seasons except summer 2010 where the fragment had the highest mean and the plantation the lowest. The control and fragment had similar mean maximum air temperatures in most months. In both winters and summers there was a significant difference in mean maximum temperatures between sites. The plantation had the lowest mean and maximum air temperatures across all seasons.

The control site had the lowest mean minimum temperature through all seasons and the only significant difference between sites was in winter 2009. The plantation and fragment had similar mean minimum air temperatures across all seasons.

5.2.7 Humidity and water vapour pressure deficit

Mean, maximum and minimum humidity were higher in the plantation in all seasons (Fig. 5.7). The control and fragment had similar mean humidity levels during all seasons. No significant differences occurred between sites.

Vapour pressure deficit (VPD) was lower in the plantation in all seasons (Fig. 5.8). The fragment was similar to the control site in each season.

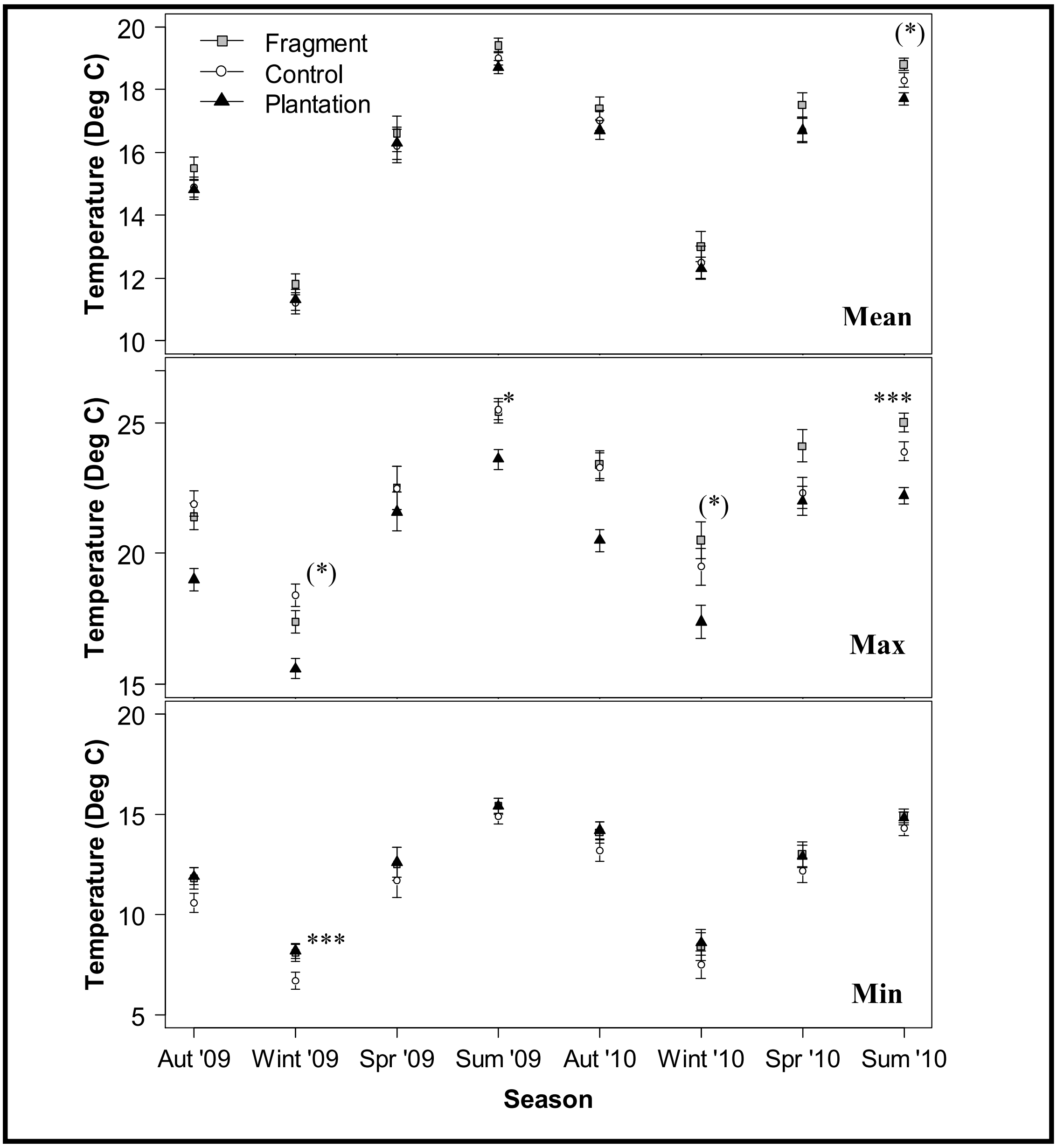

Figure 5.6: Overall mean, mean maximum and mean minimum air temperatures, asterisk indicates a significant difference between sites ((*) = p<0.05, *= p<0.01, *** = p<0.0001)

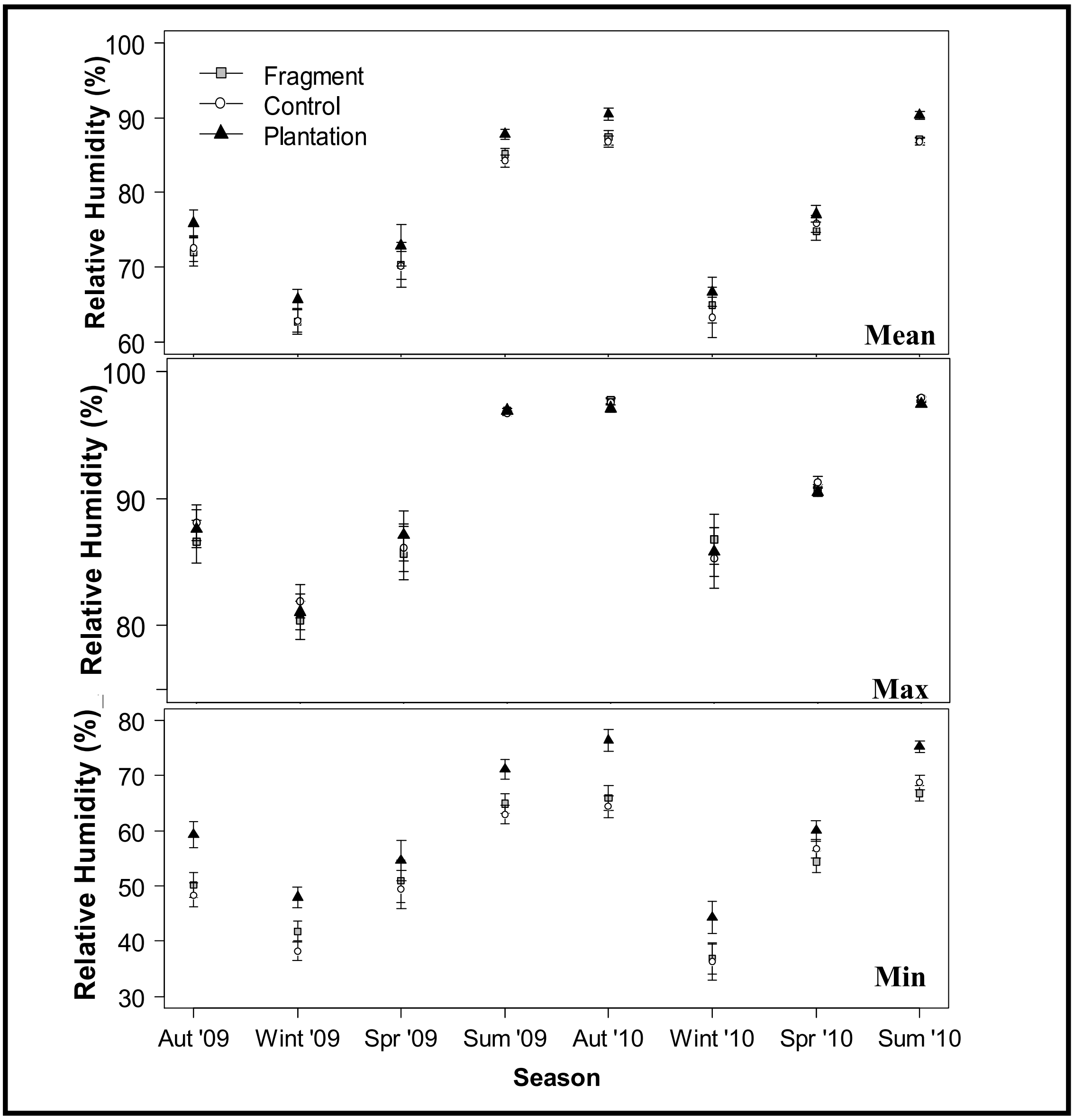

Figure 5.7: Overall mean, mean maximum and mean minimum humidity

5.2.8 Wind speed

The wind speed was much lower in the plantation in all seasons (Fig. 5.9). The fragment had a similar mean wind speed to the control during 2009 but differed in 2010. Significant differences between sites were measured across all seasons.

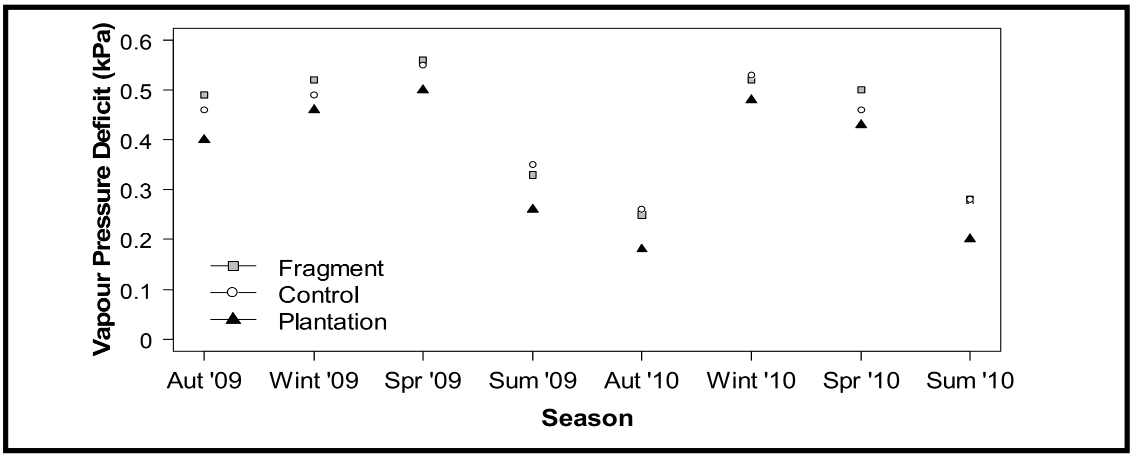

Figure 5.8: Mean vapour pressure deficit

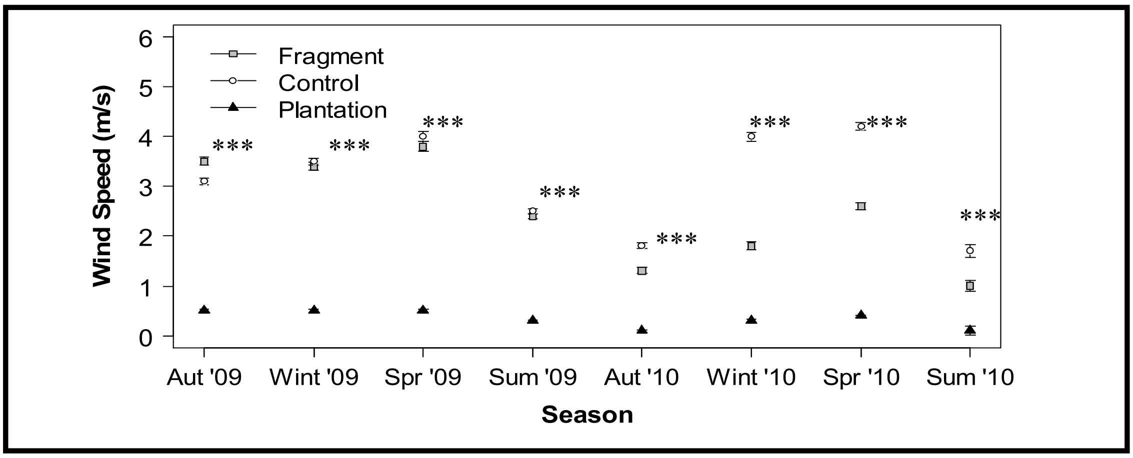

Figure 5.9: Mean wind speed, *** indicates a significant difference between sites ($p<0.0001$)

5.2.9 Solar irradiance

Solar irradiance was lower in the plantation in all seasons (Fig. 5.10) and the biggest differences were in winter where the mean irradiance in the plantation was as low as 4.8% of the control site. The control site had a higher mean and maximum irradiance in all seasons. Mean irradiance in the fragment was similar to the control in all seasons except the winters of 2009 and 2010.

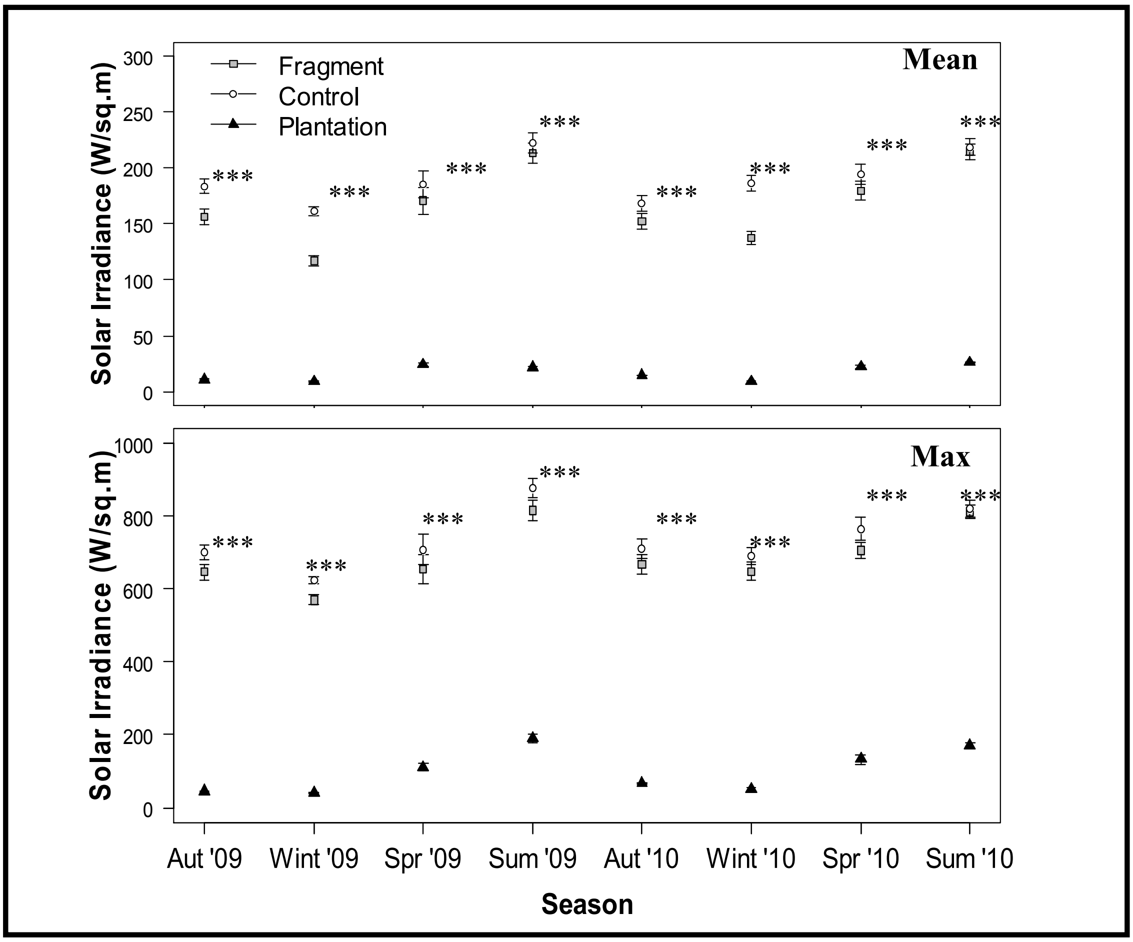

Figure 5.10: Overall mean and mean maximum solar irradiance, asterisk indicates a significant difference between sites (*** = p<0.0001)

5.2.10 Soil Moisture

Soil moisture was highest in the control sites in all sampling periods except March 2009 and September 2010 (Fig. 5.11). The plantation sites had the lowest soil moisture in all sampling periods except September and December 2010. Significant between-site differences occurred in four of the seven sampling periods.

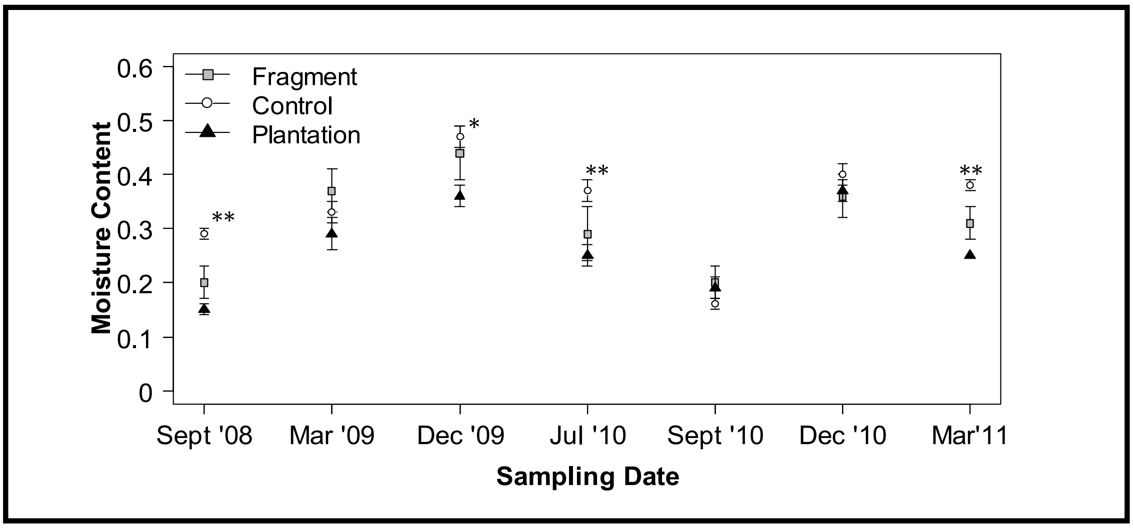

Figure 5.11: Mean soil moisture, asterisk indicates a significant difference between sites (* = p<0.01, ** = p<0.001)

5.2.11.1 Soil temperature 2cm

Mean soil temperature values at 2cm below the surface in the control site were similar to those in fragments in all seasons (Fig. 5.12). Significant between-site differences were measured for all seasons, although the mean soil temperature appeared similar for all sites in winter 2010. The biggest difference was in the summers of 2009 and 2010 where mean soil temperatures in the plantation sites were lower than the fragments by 4.13 ºC and 4.37 ºC respectively. Across all seasons, the plantation sites had the lowest mean maximum soil temperature and significant between-site differences occurred. In autumn and winter 2010, the gap between mean maximum soil temperatures in the plantation sites and in the other sites was smaller. Significant between-site differences for mean minimum soil temperature occurred in all seasons except spring 2009 and summer 2010. Mean minimum soil temperature in the plantation sites was respectively 2.20 ºC and 3.38 ºC higher than the control site in autumn and winter 2010, and was similar to the fragments in autumn 2010. Grassland fragment E2 had the warmest recorded soil temperature (55.5ºC) which occurred in September 2012 and the lowest (1.9 ºC) was in the control site in June 2010.

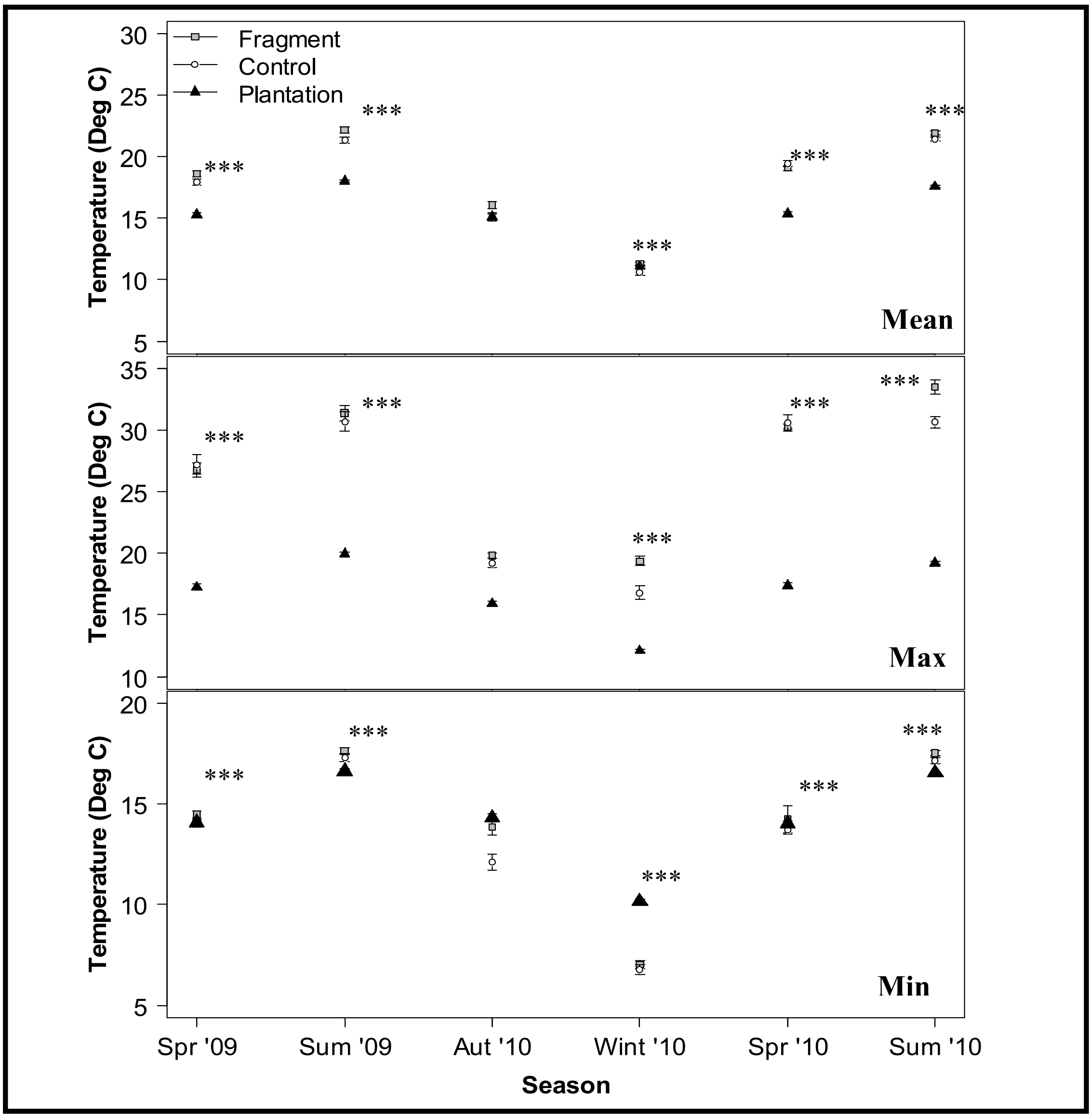

Figure 5.12: Mean soil temperature at 2cm below soil surface, asterisk indicates a significant difference between sites (*** = p<0.0001)

5.2.11.2 Soil temperature 10cm

Significant between-site differences occurred in most seasons for mean, maximum and minimum soil temperatures at 10cm below the soil surface (Fig. 5.13). The plantation sites had a lower mean temperature in all seasons except autumn and winter 2010 while the fragments had the lowest mean soil temperature in winter 2010. Highest mean soil temperatures occurred in the fragments in spring and summer 2009, differing from the plantation by 2.97 ºC and 4.12 ºC respectively; while the control had the highest in spring and summer 2010, differing from the plantation by 3.84 ºC and 3.88 ºC respectively. Mean maximum soil temperatures were highest in the control in all seasons and lower in the plantation in all seasons except winter 2010. The biggest differences occurred in the summers of 2009 and 2010 where the plantation sites were respectively 8.41 ºC lower than the fragments and 7.64 ºC lower than the control site. Mean minimum soil temperatures were lowest in the plantation in all seasons except autumn and winter 2010. Lowest mean minimum soil temperature occurred in the fragments in winter 2010.

5.3 Overall mean results

While there was no significant difference in the overall mean for P and Na (Table 5.2), most mean soil values within the fragments were in between those of the control and the plantation sites (Table 5.2). Some mean values in the fragments, such as extractable N, nitrate and Mg, were closer to those in the plantation than the control sites. Mean K and Ca concentration over all seasons was significantly different between sites with the plantation sites having the lowest K and highest Ca (Table 5.2)

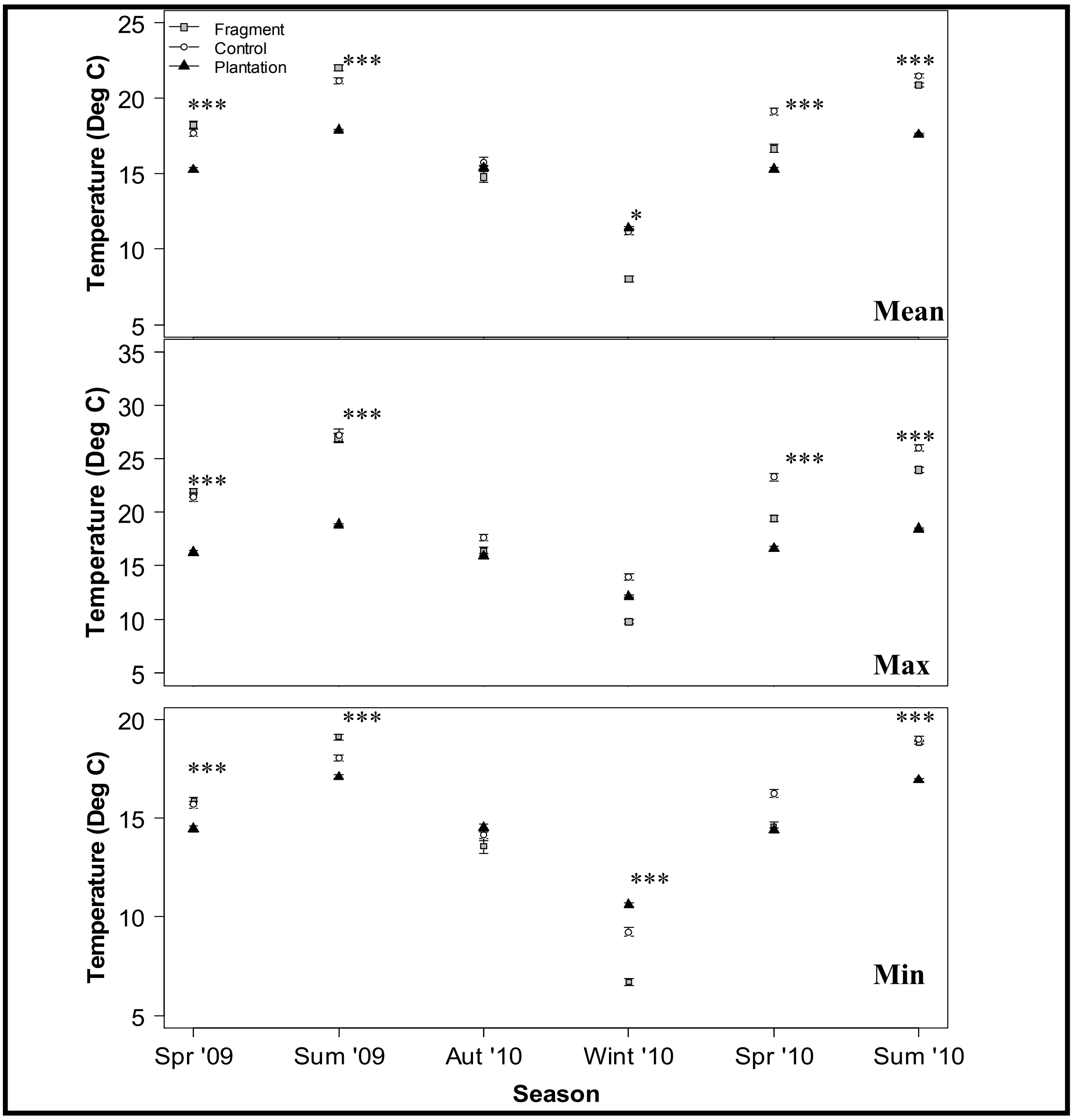

Figure 5.13: Mean soil temperature at 10cm below soil surface, asterisk indicates a significant difference between sites (*= p<0.01, *** = p<0.0001)

Conversely, mean microclimate values within the fragments were closer to the control sites than the plantation sites, and some values, such as air temperature and VPD, were higher than in the control sites (Table 5.2). Mean soil temperature at 2cm was highest in the fragments.

Table 5.2: Means and F values across all seasons for extractable N, nitrate, ammonium, pH, P, Organic C, K, Ca, Mg, Na, air temperature, relative humidity, vapour pressure deficit, wind speed, solar irradiance, soil temperature and soil moisture, Degrees of freedom = 2, asterisks indicate significant between-site differences (*p<0.01, **p<0.001, ***p<0.0001)

	Control sites	**Fragments**	**Plantation**	**F value**
Extractable N (ppm)	21	37	41	8.029**
Nitrate (ppm)	4	26	22	16.282***
Ammonium (ppm)	17	16	16	0.030
pH	4.6	4.5	4.4	5.093*
P (ppm)	3	3	3	0.995
Organic C (%)	4.2	4.5	4.8	0.908
K (ppm)	130	104	72.1	16.158***
Ca (ppm)	1031	1280	1520	7.537**
Mg (ppm)	352	698	622	18.355***
Na (ppm)	14	16	17	1.046
Air Temperature (ºC)	15.7	16.3	15.6	0.146
Relative Humidity (%)	75.3	75.5	78.4	0.236
Vapour Pressure Deficit (kPa)	0.42	0.43	0.37	0.726
Wind Speed (m/s^2)	3.1	2.5	0.3	364.574***
Solar irradiance (W/m^2)	190.1	167.7	17.2	125.130***
Soil Temperature 2cm (ºC)	17.6	18.2	15.4	0.973
Soil Temperature 10cm (ºC)	17.7	16.8	15.5	0.507
Soil Moisture	0.34	0.32	0.27	1.096

5.4 Boundary effects

5.4.1 Shading

At the local noon during the June solstice, more than 50% of the small fragment (E8) is in shade (Table 5.3). At the same time, just under 30% of E2 is in shade.

Table 5.3: Shading in E8 and E2 during the December and June solstices and equinoxes in March and September and maximum area under shade

Fragment	**Tree Height (m)**	**Slope (º)**	**Shade length (m): Equinox**	**Shade length (m): December Solstice**	**Shade length (m): June Solstice**	**Maximum area (m^2) and percentage in shade at local noon**
E8	18	9	9.57	0.79	25.9	1295 / 51.8
E2	19	18	11.5	0.87	37.2	4650 / 29.8

5.4.2 Pine needles

In E8, sample points 1 and 3 in transects A and C had higher pine needle masses than in location 2 (Fig. 5.14). Sample point 2 in A and C had no pine needles. The centre point of E8, which was sample point B3, had 0.1g of pine needles. E2 had the highest pine needle mass of 7.5g in sample point A1 (not shown on Fig. 5.14). There were no pine needles in the rest of the sample points on transect A in E2. Transects B and C in E2 had higher pine needle masses in upslope and downslope sample points (1 and 5) than the middle sample points (2, 3 and 4). There were pine needles in all sample points on transect C and in all but sample point 3 on transect B.

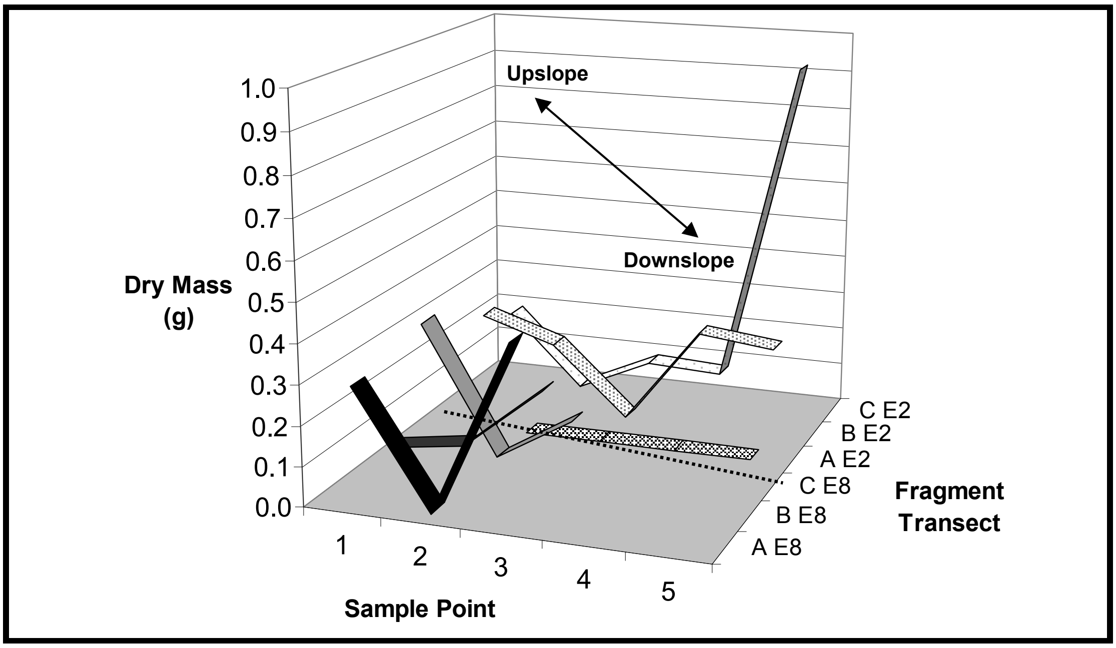

Figure 5.14: Pine needle mass in fragment E2 and fragment E8 (value of 7.5g for A1 in E2 was removed to improve graph clarity), line on base separates the values for the 2 fragments

CHAPTER 6: DISCUSSION

6.1 Within-site and between-site results

The lack of significant differences between sampling points within a specific site indicates that the soil chemical properties in the fragments do not vary substantially. Only potassium and calcium exhibit within-site differences (Table 6.1). The difference in Potassium in E8 may be due to the very narrow range of high values at sampling point B in comparison to the other sampling points (Fig. A.7). The difference between the highest and lowest value at sampling point B is 30ppm and the mean is 145ppm. The lack of variation in potassium is unique to this sampling point as the other seven sampling points in E2 and E8 differ by a minimum of 57ppm (point C in E8) to a maximum of 138ppm (point C in E2). The mean is also high as the means for the other seven sampling points are between 85ppm (A in E8) and 108ppm (D in E2). It is unclear why sampling point B had higher potassium values than the other three sampling points as the pine needle litter was lower near B (B2, Fig. 5.14) and near A (A1, Fig. 5.14) and C (A3, Fig. 5.14) and other cations did not exhibit a similar pattern. The difference in calcium in E2 may be due to the consistently high values at sampling point A (Fig. 5.2 and Fig. A.7) when compared to sampling points B, C and D. There was no result for sampling point A in September 2008 and this may have contributed to skewing the values and leading to a statistically significant difference. If the highest value from the other three sampling points in September 2008 (864 ppm) is inserted as the value for point A, and an ANOVA is conducted on the new dataset, the result is no significant difference. However, there is no result for point A in fragment E2 for September 2008 for any parameter. The calcium values may therefore be different at each sampling point in the fragment. The reason for this difference in calcium is unlikely to be pine needle litter as the mass of pine needles found near sampling point A (B2, Fig. 5.14) was lower than near B (B4, Fig. 5.14) while C (C3, Fig. 5.14) and D (A3, Fig. 5.14) had the lowest of the four sampling points. Such a variance in pine needle mass should cause similar differences in the other cations.

Table 6.1: The parameters where significant differences were observed from the analyses of with-in site, between site, seasonal and overall mean results. Mean values for a parameter are reported for the with-in site, between site and overall mean categories of analysis. F values and significance are reported alongside. Only F values and significance are reported for the seasonal category of analysis. Asterisks indicate significance ((*)p<0.1, *p<0.01, **p<0.001, ***p<0.0001), Df = degrees of freedom, NS = not sampled, shaded cells indicate no significant difference

With-in site (Df = 3)			
Parameter	**Fragment E8**	**Fragment E2**	**F value**
K (ppm)	106		2.610*
Ca (ppm)		1214	2.701*
Between Site (Df = 3)			
Parameter	**Fragment E8**	**Fragment E2**	**F value**
Extractable N (ppm)	55	25	19.034***
Nitrate (ppm)	39	9	36.076***
Organic C (%)	5.3	3.6	5.037*
Soil Moisture	0.38	0.26	10.815**

Seasonal (Df = 2)								
Parameter	**Spr'08**	**Aut'09**	**Win'09**	**Spr'09**	**Sum'09**	**Aut'10**	**Win'10**	**Spr'10**
Extractable N	9.48**	12.7**	NS	NS	6.30**	NS	5.80**	NS
Nitrate	11.5**	8.70**	NS	NS	6.77**	NS	4.54*	NS
Ammonium	3.58*		NS	NS		NS		NS
Organic C			NS	NS	12.8***	NS		NS
P		10.5**	NS	NS		NS	4.44*	NS
pH	11.9**	0.047	NS	NS		NS	4.96*	NS
K	9.19**		NS	NS		NS	35.3**	NS
Ca			NS	NS	5.41*	NS		NS
Mg	0.03*	9.33**	NS	NS	7.13**	NS	6.57**	NS
Na			NS	NS		NS	2.76(*)	NS
Parameter	**Aut'09**	**Win'09**	**Spr'09**	**Sum'09**	**Aut'10**	**Win'10**	**Spr'10**	**Sum'10**
Mean Air Temperature								9289(*)
Max Air Temperature		1475(*)		6663*		1517(*)		4713***
Min Air Temperature		888***						
Wind Speed	1927***	821***	752***	524***	556***	327***	156***	221***
Mean Solar Irradiance	349***	320***	180***	681***	321***	344***	724***	597***
Max Solar Irradiance	733***	614***	361***	1193***	532***	1552***	984***	1329***
Mean Soil Temp 2cm	NS	NS	1903***	12095***		18.0***	4034***	11794***
Max Soil Temp 2cm	NS	NS	1844***	4133***		34.6***	2485***	4592***
Min Soil Temp 2cm	NS	NS	632***	13357***		414***	1383***	10172***

Mean Soil Temp 10cm	NS	NS	243***	8451***		36***	63***	15056***
Max Soil Temp 10cm	NS	NS	2220***	4427***			2894***	13182***
Min Soil Temp 10cm	NS	NS	51***	11890***		156***		14381***
Parameter	**Spr'08**	**Aut'09**	**Win'09**	**Sum'09**	**Win'10**	**Spr'10**	**Sum'10**	**Aut'11**
Soil Moisture	11.9**		NS	3.51*	5.90**			7.61**
Overall Mean (Df = 2)								
Parameter	**Control sites**		**Fragments**		**Plantation sites**		**F value**	
Extractable N (ppm)	21		37		41		8.029**	
Nitrate (ppm)	4		26		22		16.282***	
pH	4.6		4.5		4.4		5.093*	
K (ppm)	130		104		72.1		16.158***	
Ca (ppm)	1031		1280		1520		7.537**	
Mg (ppm)	352		698		622		18.355***	
Wind Speed (m/s^2)	3.1		2.5		0.3		364.574***	
Solar Irradiance (W/m^2)	190.1		167.7		17.2		125.130***	

Fragment E2 and E8 differ from each other with respect to N, nitrate, SOC and soil moisture (Table 6.1). The difference in N is due to the large difference in nitrate values. Mean nitrate in E8 is more than double the nitrate values in E2. This may be due to the higher SOC and moisture levels in E8 than in E2 which leads to a higher nitrogen mineralisation rate (Louw and Scholes, 2002). The moisture levels may be higher in E8 due to the lower soil temperatures as there is a higher percentage of shading than E2 (Table 5.3).

6.2 Seasonal results

6.2.1 Soil physical and chemical properties

6.2.1.1 Nitrogen

The introduction of pines causes a shift in available nitrogen from nitrate to ammonium and from mineral N to predominantly organic N (Scholes and Nowicki, 1998). Ndala *et al.* (2006) found that higher N mineralization rates occurred in the month of September under plantations than under grassland on clayey, dolomitic derived soils. As the wet season progressed, rates of N mineralisation under grassland and plantation equalised. Higher rates of N cycling occur in conditions of higher temperatures and soil moisture, it is thus expected that extractable N content, which is a sum of the NH_4^+ and NO_3^- concentrations, at Groenvaly, should be highest in the summer and autumn months (December and March) and lowest in the spring and winter months (September and July). The consistently low extractable N values in the control sites are supported by Davis (1998), Farley and Kelly (2004) and Ndala *et al.* (2006) but are contrary to Tate *et al.* (2007). Extractable N values for the fragment sites were higher than the control in all seasons and only lower in the plantation in autumn (March). This suggests that the plantation has an elevating affect on N mineralisation in the fragment.

Many authors have reported a decrease in total N stocks under a pine plantation relative to adjacent grassland (Parfitt *et al.*, 1997; Chen *et al.*, 2003; Guo *et al.*, 2008; Kirschbaum *et al.*, 2008). The decreases in total N in these studies may be attributed to mineralisation of organic N into the inorganic forms (NH_4^+ and NO_3) which are subsequently taken up by the trees or leached out of the soil. N mineralisation is influenced by temperature, soil organic C levels, soil pH, soil P levels, soil water content and aeration, soil mineralogy and texture and the C/N ratio of the organic material (Louw and Scholes, 2002). Figure 6.1 illustrates the interaction of these factors. High levels of organic C in a warmer environment (mean annual air temperature above 16°C) resulted in the highest N mineralisation rates in the Mpumalanga plantation (Louw and Scholes, 2002). At Groenvaly the mean annual air temperature is 19°C and the organic C levels were consistently above 3% which provides an ideal environment for high N mineralisation. The low pH measured at Groenvaly results in anion retention capacity which would assist in the retention of nitrate anions, amongst others (Farley and Kelly, 2004). Nitrogen mineralisation may be in excess of plant needs, especially if growth is phosphorous-limited rather than nitrogen-limited (Farley and Kelly, 2004), and when ammonification exceeds plant demand, large pools of soil nitrate persist (Farley and Kelly, 2004). The September soil sampling was completed before the rains arrived in 2008, hence, before the N mineralisation rates had begun to increase. Total available N in the fragments is highest in winter and spring and is mainly due to the high nitrate values.

N mineralisation rates in the grassland fragments may be higher than the control grassland sites due to lower pH and higher organic C. If fragment E2 was considered in isolation, the N levels would be similar to the control grassland. N and nitrate values in E8 are particularly high (Table 5.1), which is possibly due to the higher SOC and moisture and similar soil temperature at 2cm. The impact of the plantation on the N mineralisation rate is therefore more evident in the smaller fragment E8.

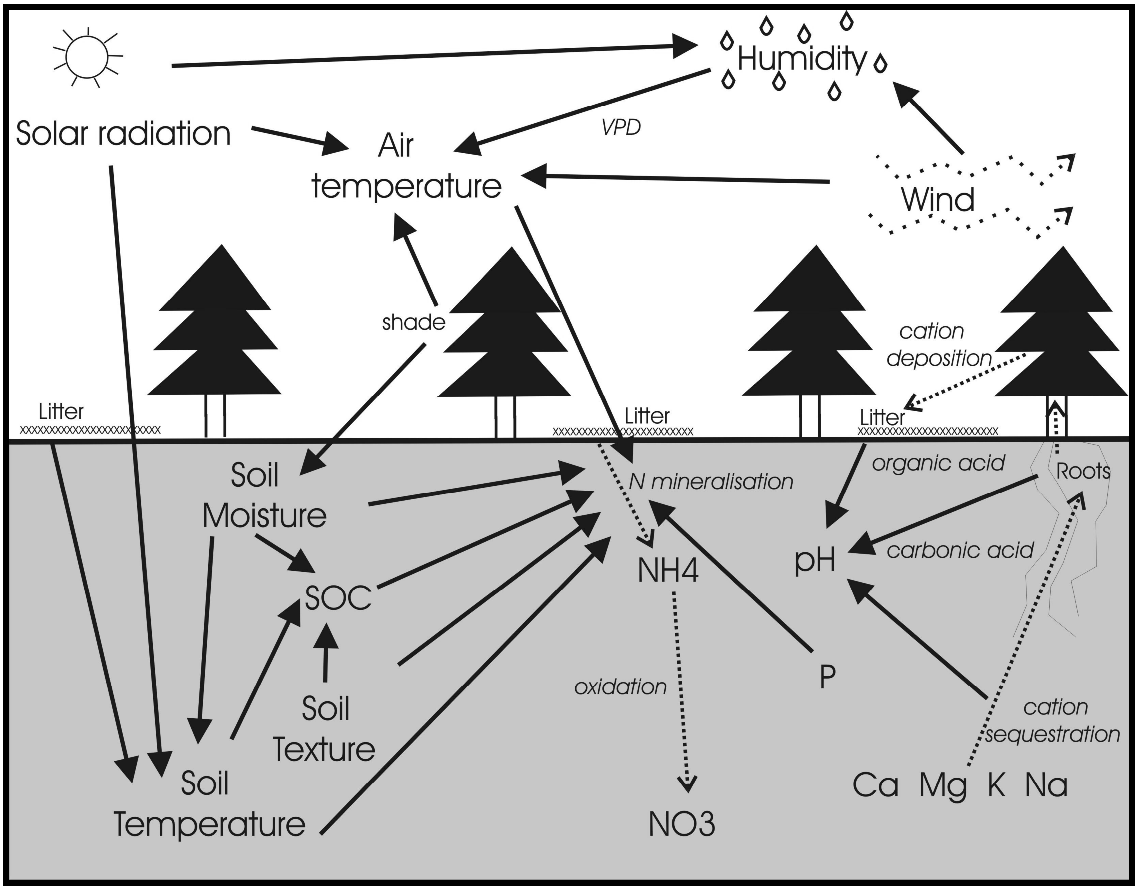

Figure 6.1: The interaction of soil and microclimate factors in a pine plantation

6.2.1.2 Soil Organic Carbon

An initial decline in soil organic carbon (SOC) in pine plantations is to be expected (Paul *et al.*, 2002; Guo *et al.*, 2008; Kirschbaum *et al.*, 2008), however, SOC results at Groenvaly indicate insignificant differences between sites. Factors that may affect SOC levels following afforestation are plantation type, site preparation, previous land use, climate, clay content and site management techniques (Paul *et al.*, 2002). Groenvaly was previously a pastureland that it did not undergo any site preparation before planting and, at the beginning of the study, it had been under plantation for 14 years at the beginning of the study. Although Paul *et al.* (2002) found that SOC significantly decreased on ex-pasture sites, the affect was most notable in the first 10 years following afforestation and an increase in SOC was measured under pines when compared to eucalypts. Paul *et al.* (2002) discuss the effect of various climates on SOC following afforestation. According to Paul *et al.*'s (2002) description of climates around the world, Groenvaly would fall into the continental moist category, which should lead to an increase in SOC following afforestation. Clay content is low in the Groenvaly study sites which are composed of loamy sand, sand and sandy loam soils. The low clay content should increase storage of SOC in the top 10cm layer (Paul *et al.*, 2002). Weeds are a source of SOC (Paul *et al.*, 2002) and may contribute to SOC levels at Groenvaly where weed control is limited to invader species such as bug weed (*Solanum mauritianum*). The Groenvaly plantation was pruned after eight years, although the affects of thinning on soil C are not yet fully known (Paul *et al.*, 2002). Most of the factors identified by Paul *et al.* (2002) point to an increase in SOC in the Groenvaly plantation. It is possible that an immediate decline in SOC occurred at Groenvaly after afforestation followed by a gradual increase. SOC may increase to an extent that, after 30 years, there is a higher level of SOC under plantation than in the original soil before planting (Paul *et al.*, 2002). However, Guo *et al.* (2008) point out that drier and cooler conditions in plantations slow down both litter decomposition and organic matter decomposition. Thus, while there is a slow input of SOC in the form of organic matter, there is also a slow decomposition of organic matter in plantation soils which maintains SOC content.

The temperature and moisture dynamics in the Groenvaly plantation may be the contributing factors to the similar results for SOC in the plantation and grassland sites (Fig. 6.1). Insignificant differences in SOC between 20–year–old and 22–year–old pine and adjacent grassland were additionally found by Lilienfein *et al.* (2000) and Zhao *et al.* (2009) respectively. Davis and Lang (1991) reported an increase in SOC only in plantations older than 31 years. Litter from plantation trees may be a source of soil C, although Guo *et al.* (2008) report that above ground litter decomposition did not contribute significantly to C concentrations in the mineral soil under their plantation. Drier and cooler conditions under the canopy slow down litter decomposition and result in low contributions to soil C and N (Guo *et al.*, 2008). SOC in the fragment sites was similar to the plantation in all seasons except summer where it was lower than both the control and plantation sites. Fragment E8 had consistently higher SOC than E2 and thus appears to have been influenced more by the plantation than the larger fragment E2. The lower soil moisture in fragment E2 compared to both E8 and the control sites may have contributed to this difference.

6.2.1.3 Phosphorous

The Bray–1 method (Agri Laboratory Association of South Africa, 2004) for Phosphorous (P) was used for the analysis of the Groenvaly soils, which determines the more soluble inorganic P whereas some studies use the Olsen method that indicates the plant-available Phosphorous. P values at Groenvaly did not exceed 4ppm which is a similar finding to other studies (Davis and Lang, 1991; Chen *et al.*, 2000, 2003). Although, Zhao *et al.* (2007, 2009) reported values in excess of 70ppm in sandy soil under plantations of Mongolian pine (*Pinus sylvestris* var. *mongolica*). There were statistically significant differences between sites only in autumn and winter (March and July). In autumn, the plantation and fragment sites had higher inorganic P while in winter the control and fragment had higher values than the plantation. The former observation coincides with some studies (Chen *et al.*, 2000, 2003) and the latter with other studies (Davis and Lang, 1991; Zhao *et al.*, 2007, 2009). Chen *et al.* (2000, 2003) also conducted soil sampling in autumn which may be the reason for similar results. However, Zhao *et al.* (2007, 2009) and Davis and Lang (1991) conducted spring, and not winter, soil sampling. The overall mean inorganic P was the same for all sites at Groenvaly. The lack of significant differences in the overall mean results may be due to the younger plantation age at Groenvaly, as Davis and Lang (1991) and Chen *et al.* (2000, 2003) reported large differences between grassland and plantations of 31 and 19 years respectively. Plantation age is an important consideration as the process of incorporation of P from organic matter into the mineral soil can take a number of years (Chen *et al.*, 2008). The fragments had similar inorganic P values to the control in all seasons except autumn where it was similar to the plantation and 1 ppm higher than the control site. The higher P in the fragments may be due to the elevated litterfall input which occurs in the plantation in autumn, some of which settles on the fragments (Fig. 5.14).

6.2.1.4 pH

Soil pH was significantly higher in the control sites only in spring and winter. This decline in pH in the plantation sites is consistent with findings in other studies on pine and adjacent grassland sites (Parfitt *et al.*, 1997; Alfredsson *et al.*, 1998; Lilienfien *et al.*, 2000; Groenendijk *et al.*, 2002; Scott *et al.*, 2006; Tate *et al.*, 2007; Singh *et al.*, 2009). Larger differences in pH between grassland and pine are evident with increasing plantation age (Davis and Lang, 1991; Zhao *et al.*, 2007; Macdonald *et al.*, 2009). Although there were no significant differences during the wetter months of the year, the plantation continued to have the lowest pH value. The plantation appears to have had a lowering effect on the pH in the fragment sites which is possibly due to the pine needle litter which settles on the fragment. Organic acid input and cation redistribution are the two likely mechanisms responsible for the decrease in pH under plantation as they are active in the first 10cm of mineral soil (Fig. 6.1). The third mechanism, proposed by Jobbágy and Jackson (2003), is sequestration and redistribution of cations from acidic litter and is active in the deeper soil layers.

The largest decline in pH is often associated with the loss of exchangeable base cations and increases in exchangeable Aluminium (Jobbágy and Jackson, 2003). At Groenvaly, base cation concentration in the plantation sites is lower in spring and winter than in summer and autumn. Because organic acid input and resultant cation leaching is more active in the wetter months it is likely that cation redistribution is the acidifying mechanism in the colder and drier months. During the colder months, cations are drawn down to the root zone for nutrient uptake but inputs from litterfall and throughfall are low. Cation concentration in the top 10cm of the mineral soil thus decreases over winter to a minimum in spring and results in increased acidification. This mechanism is active to a lesser extent in the fragments as the balance of nutrient demand and litterfall volumes is smaller.

6.2.1.5 Major cations – K, Ca, Mg, Na

The high values of K, Ca, Mg and Na in the control sites in July 2010 may be due to the re-deposition in soil following the burning which occurred a few weeks prior to sampling. The consistently higher Ca and Mg in the plantation and fragment sites compared to the control sites may be due to nutrient uptake from the lower horizons and subsequent deposition through litterfall (Fig. 6.1). Davis (1998) found that stands older than 15 years have similar or higher K, Mg and Ca values to adjacent grassland. Throughfall in plantations downwind of industrialised regions can contribute substantially to these values (Olbrich *et al.*, 1993). Olbrich *et al.* found enhanced nutrient concentrations in throughfall sampled in afforested regions of Mpumalanga relative to rainfall samples taken in open areas. The throughfall was particularly enhanced with nitrate, K, Ca and Mg ions. Fragment and plantation Mg and Ca values may be similar due to a lower nutrient requirement by the vegetation in the fragment while there is some input of cations from the adjacent plantation. The higher Na values under pine in summer and autumn is consistent with findings in other studies (Parfitt *et al.*, 1997; Alfredsson *et al.*, 1998; Lilienfein *et al.*, 2000), which suggest that the reasons are nutrient cycling from lower horizons. Na concentration was, however, similar in all sites in spring and higher in the fragment sites than the plantation sites in winter. The high values in winter may be due to the high input of Na from litterfall (Fig 5.14) and low nutrient uptake from the dormant vegetation. The significantly lower concentration of K is supported by results from Alfredsson *et al.* (1998), Davis (1998) and van Wesenbeeck *et al.* (2003) under plantations 17 years old and younger. In studies where higher values for K under plantation than under adjacent grassland are reported, plantations were older than 20 years. It is possible that K cycling rates at Groenvaly are slower than Mg, Ca and Na cycling rates.

6.2.2 Air microclimate

6.2.2.1 Wind speed

The plantation substantially lowers wind speed, a result which is supported by Hawke and Wedderburn (1994). Higher wind speeds in the control in winter and spring 2010 may be due to the burning which occurred in July 2010. As vegetation re-established in the summer, the wind speed was lowered. The wind speed in the fragments does not appear to be affected by the surrounding plantation.

6.2.2.2 Humidity and water vapour pressure deficit

Both mean and minimum humidity levels were highest and VPD levels were lowest in the plantation in all seasons, although not significantly so. Maximum humidity levels were similar for all sites in all seasons. This indicates that the plantation had a very small moderating effect which is contrary to the findings of Selleck and Scuppert (1957). The climate of Selleck and Schuppert's (1957) study area differed from Groenvaly as it was in an area of high humidity variation with a range of 100% to 8%. Groenvaly humidity varies from a minimum of 27% in winter to a maximum of 99% in summer. The smaller range in humidity may contribute to the similar humidity levels at each site. Higher VPD levels in a grassland compared to an adjacent plantation is supported by Holl (1999), Newmark (2001) and Porté *et al.* (2004). The fragment and control had similar humidity and VPD levels in all seasons; the plantation therefore does not appear to have an impact on humidity or VPD in the fragment.

6.2.2.3 Air temperature

Extremes in maximum and minimum air temperatures are moderated by the plantation. The moderating effect is particularly noticeable in autumn where the fragments and control sites had similar maximum air temperatures while the maximum air temperature in the plantation was up to 2.9ºC lower. Minimum air temperatures were less affected by the plantation as the biggest difference was in winter where the minimum temperatures in the plantation were 1.1ºC to 1.5ºC higher than the control sites. These results are supported by those from Silva-Pando *et al*. (2002), Porté *et al*. (2004) and Gea-Izquierdo *et al*. (2009). Higher minimum temperatures were recorded in the fragments than the plantation throughout the monitoring period. This suggests that the surrounding plantation had a warming effect on the microclimate in the fragments. Maximum temperatures in the fragment where lower than the control site for the first 12 months but were higher for the second 12 months. The former is to be expected while the latter may be due to a combination of a lower wind speed for the 2010 seasons and a slightly warmer year than the prior year. Lower wind speeds may have led to a reduction in air mixing, which combined with elevated temperatures, may have created a warmer environment within the fragment.

6.2.2.4 Solar irradiance

Solar irradiance in the plantation is substantially lower than in the grassland fragment and control site. Solar irradiance in the plantation was as low as 4.8% of that in the control, which is much lower than values discussed in Benevides *et al*. (2009). This difference is most probably due to the stems per hectare (sph) which is 1750 at Groenvaly and ranges from 100 to 625 sph in the studies referred to by Benavides *et al*. (2009). The fragment only differs from the control in winter with respect to mean solar irradiance. In winter, because the sites are orientated to the south-west on a hillside, the shading effect from the plantation is increased. The Davis Weather Station in grassland fragment E8 was in shade at local noon during the June Solstice (Table 5.3). Maximum solar irradiance levels are however similar in the control and the fragment. The plantation therefore only has an impact on the solar irradiance in the fragment in winter.

6.2.3 Soil microclimate

6.2.3.1 Soil moisture

Plantation sites had the lowest moisture content in all but 2 sampling periods which is supported by other studies (Parfitt *et al*., 1997; Farley *et al*., 2004; Tate *et al*., 2007; Guo *et al.*, 2008; Macdonald *et al*., 2009). The lower soil moisture can be attributed to greater transpiration, greater evaporation of intercepted rainfall (Le Maitre *et al.*, 1996) and greater water use by trees than grassland (Fahey and Jackson, 1997). Lower soil moisture in the control sites in July 2010 is most likely due to the planned burning which occurred in early July 2010 which resulted in bare soil and more evaporation. By summer

(December) the moisture was slightly higher than the fragments and plantation as vegetation had been re-established. Soil moisture in the fragments was higher than the plantation and lower than the control sites on all occasions except two. The drier plantation may decrease the amount of run-off entering the fragments and thus could have a lowering affect on the soil moisture in the fragments. Moisture levels in Fragment E8 were similar to the control sites, but values in E2 were lower. This suggests that the plantation maintains moisture conditions in the smaller fragment by providing some shade and preventing evaporation. The larger fragment E2 receives both a smaller percentage of shade and less run-off, resulting in a drier soil.

6.2.3.2 Soil temperature

A consistently lower mean soil temperature under tree canopy compared to grassland is a common result (Hawke and Wedderburn, 1994; Parfitt *et al*., 1997; Scull, 2007; Guo *et al*., 2008). A narrowing of the range in soil temperatures is evident as minimum soil temperatures were similar while maximum soil temperatures were lower than the control and fragment sites. This observation is supported by other studies (Silva-Pando *et al*., 2002; Porté *et al*., 2004; Gea-Izquierdo *et al*., 2009).

6.2.3.2.1 Below surface – 2cm

A variation of soil temperature under the plantation compared to the control site of 4.37 ºC is a similar finding to Guo *et al*. (2008) who measured an average variation of 4ºC at 5cm, 20cm and 45cm below the soil surface. Although there is shading in the fragments due to the plantation, the fragment and control sites have similar soil temperatures at 2cm below the surface in all seasons. The plantation thus does not appear to have an impact on the soil temperatures at 2cm below the surface in the fragments.

6.2.3.2.2 Below surface – 10cm

Soil temperature at 10cm follows a similar pattern to the values for soil temperature at 2cm, which is a similar result to other studies (Parfitt *et al*., 1997; Porté *et al*., 2004). One main exception is winter where mean, maximum and minimum soil temperatures in the fragment were lower than both the plantation and the control. In winter, the fragments receive less solar irradiance than the control sites and more shading which covers just over 50% of E8 and 30% of E2 at the June solstice (Table 5.3). In fragments E8 and E2, the upslope locations of the iButtons™, that measured soil temperature, would be in shade at local noon for part of the year. During the June solstice, two additional iButton™ locations would be in shade at local noon. This shading appears to cause the deeper layer of soil to stay cooler in the winter months. Solar irradiance that does reach the surface in the fragment is not sufficient to warm the soil below a depth of 2cm and the fragment does not have the insulating pine needle layer which may retain heat at night. Additionally, minimum air temperatures in the plantation are warmer than the fragment and this may result in fewer days of frost in the plantation. This results in lower soil temperatures in the fragment when compared to the control site and plantation sites. The plantation therefore has a lowering effect on soil temperatures at 10cm below the surface in the fragment.

6.3 Overall mean results

The overall mean values for soil chemistry in the fragments tend to lie between the plantation sites and the control sites, and in some cases these are very similar to the plantation sites (Table 5.2). Mean extractable N, SOC and pH in grassland were also found to be similar to adjacent plantation sites in the study of Ndala *et al.* (2006) and mean inorganic phosphorous was similar at adjacent grassland and Mongolian pine sites (Zhao *et al.*, 2009). However, the mean results of Chen *et al.* (2003) for N, inorganic P and SOC in grassland and adjacent plantation were not similar. Overall mean results suggest that the chemistry within the fragments has been altered by the surrounding plantation. When compared to the seasonal results, however, the impact is not consistent throughout the year (Table 6.1). Extractable N is significantly higher in the fragments in all seasons except autumn. SOC is only significantly different from the control sites and plantation sites in summer. Significant differences occur in P results for autumn and winter and pH results in spring and winter (Table 6.1). Table 6.1 shows that there are significant differences in cation results in one (Ca and Na), three (K) and four seasons (Mg).

Mean results show that over a two year period, the microclimate within the fragments was not statistically different from the control site and thus did not appear to be impacted by the surrounding plantation (Table 5.2). The significant difference indicated for mean solar irradiance and mean wind speed is due to the very low values for the plantation. As is the case with soil chemistry, seasonal results indicate that there is an impact in certain seasons. When comparing the fragments and control sites, maximum air temperatures were higher in winter and summer 2010, solar irradiance was lower in the two winters and soil moisture was higher in March 2009 in the fragments. Soil temperature at 10cm below the soil surface was lower than both the plantation and control sites in winter.

CHAPTER 7: CONCLUSION

The results of this study indicate that microclimate and soil in the Groenvaly grassland fragments are impacted by afforestation. Effects of afforestation on the grassland fragments are evident across individual, seasonal and overall mean results but are not consistent for all parameters.

The values within the grassland fragments for all chemical soil parameters were not significantly different, except for P and Ca. The chemical properties of the soil within the fragments are thus fairly uniform. Mean SOC is higher in the fragments than the control sites, and this may be a contributing factor to the increased N mineralisation rates (Louw and Scholes, 2002). Warmer soil and air temperatures in the fragments compared to the adjacent plantation would also assist higher N mineralisation rates (Fig. 6.1). In winter, maximum surface temperatures and SOC were highest in the fragments which would have contributed to the highest extractable N of the three sites. However, the control sites had higher soil temperatures and lower nitrate values across most seasons, which suggest that pH and SOC have more of an influence than temperature on N mineralisation at Groenvaly. The low SOC in the fragments may be due to the influence of low soil moisture levels in summer in fragment E2. The difference in soil P in the fragments compared to the control in autumn may be due to the increased litterfall from the plantation which settles on the fragments, but the lack of large significant differences between the grassland and plantation sites may be due to the young age of the plantation (Chen *et al.*, 2008). A lower pH in the fragments than in the control sites is possibly due to the combination of organic acid input and cation redistribution (Jobbágy and Jackson, 2003). Organic acid input and the resultant cation leaching from the pine needles is the main mechanism in the warmer, wetter months while the cation redistribution is more active in the colder, drier months. The adjacent plantation appears to have a mixed effect on the major cation concentrations in the fragments. Mg, Ca and Na may have been increased from litterfall input from the plantation (Davis, 1998). Some run-off from nutrient enriched throughfall may also enter the fragment (Olbrich *et al.*, 1993). Lowered

K levels are inconsistent with the other cation levels and may be due to a particularly low K cycling rate at Groenvaly.

Microclimate results indicate that a warmer year together with a reduction in air mixing due to a lower wind speed can lead to elevated maximum temperatures in the fragment sites. Mean solar irradiance in the fragment are only affected by the plantation in winter as the fragments are located on a hillside which is oriented to the south west. Soil moisture could be lowered in the fragments as the drier plantation intercepts rainfall and contributes to a decrease in the amount of run-off entering the fragments. Low temperatures at 10cm below the soil surface in the fragments in winter may be due to the lower solar irradiance levels in the fragments, shading and the lack of an insulating litter layer which may retain heat at night. The effect is particularly evident in winter where the mean temperature was 3ºC lower and the minimum temperature was nearly 4ºC lower in the fragments than the plantation.

The impact of the plantation on the fragments was not uniform through all seasons. Mean results for parameters such as organic C indicate that the plantation has an elevating affect on the fragments. However, seasonal results show that organic carbon is lower in the fragments than in the plantation sites in autumn and summer while the reverse applies in winter and spring. Other examples are pH and P. Mean results indicate that the plantation causes a slight decrease in pH in the fragment and that P does not vary between sites. Seasonal results, however, show that all sites have the same pH in autumn and the fragments had the highest pH in summer. P also varied at a seasonal level wherein plantation sites had the highest P levels in spring, summer and autumn and the lowest in winter.

In summary, the impacts of the plantation on the soil properties, air and soil microclimate in the grassland fragments are:

- N mineralisation rates appear to be elevated and nitrate ions are better retained in the fragment.
- SOC in the fragments appears to only be affected in summer.

- Soil P in the fragments only differs from the control sites in autumn.
- The plantation appears to have a lowering effect on the pH in the fragments.
- Ca and Mg were higher in all seasons, Na was higher in summer and winter and K was lower in all seasons in the fragments than in the control sites.
- Wind speed and humidity appear to be minimally affected in the fragments.
- Minimum temperatures in the fragments were raised while the maximum temperatures were both raised and lowered.
- Mean solar irradiance levels in the fragments are only affected by the plantation in winter.
- Soil moisture was lowered in the fragments.
- Temperatures at 2cm below the soil surface are similar in the fragments and control sites. However, temperatures at 10cm below the soil surface were lower in the fragments than both the control sites and the plantation sites in winter.

Afforestation is a particular form of land-use change that is expected to continue growing (FAO, 2009). The future of afforestation research lies in the continuation of studies on soil properties and microclimate within, and adjacent to, plantations. The three challenges for afforestation research are (i) the range and intricacy of the impact of afforestation, (ii) differences in measurement and monitoring periods and (iii) a lack of focus on biomes adjacent to plantations. This Groenvaly study has attempted to address these challenges. First, conclusions on the impact of afforestation on soil properties and microclimate of natural grassland have been provided. Second, the dataset that was used covers two years of microclimate data and four seasons of soil sampling data. Third, the impact of afforestation on an adjacent biome was evaluated.

The first objective of this study was to evaluate the impact of afforestation on soil and microclimate in grassland fragments. This study has shown that overall mean values, values from just one growing season and values from one soil sampling event can lead to insufficient data and to poor conclusions. Thus, the methods and dataset must receive more focus and consideration. Evaluating possible mechanisms responsible for significant differences in soil and microclimate was the second objective. The main mechanisms that appear to be active in the grassland fragments at Groenvaly are elevated N mineralisation rates; lower moisture levels leading to lower SOC in summer; litterfall contributing to changes in Mg, Ca, Na; slower K cycling rates than expected; organic acid input and cation redistribution resulting in a lower pH; lower wind speeds leading to elevated maximum air temperatures; and aspect and shading factors causing lower solar irradiation and soil temperature in winter.

In southern Africa, grassland will remain vulnerable in the regions where climate and location are ideal for plantations; such as the escarpment (Reyers *et al.*, 2001). Fragmentation experiments, such as the one at Groenvaly, provide critical data for grassland conservation strategies. This study has highlighted that the intended goals of current grassland conservation methodologies may not be achievable if the impact of the plantations on microclimate and soil negatively affects grassland biodiversity. Further research should thus be conducted on the mechanisms leading to the observed changes and the implications of variations in microclimate and soil. Particular attention should be given to the resultant effects on insect, mammal and grassland diversity and to a subsequent revision of current grassland conservation strategies.

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APPENDIX A

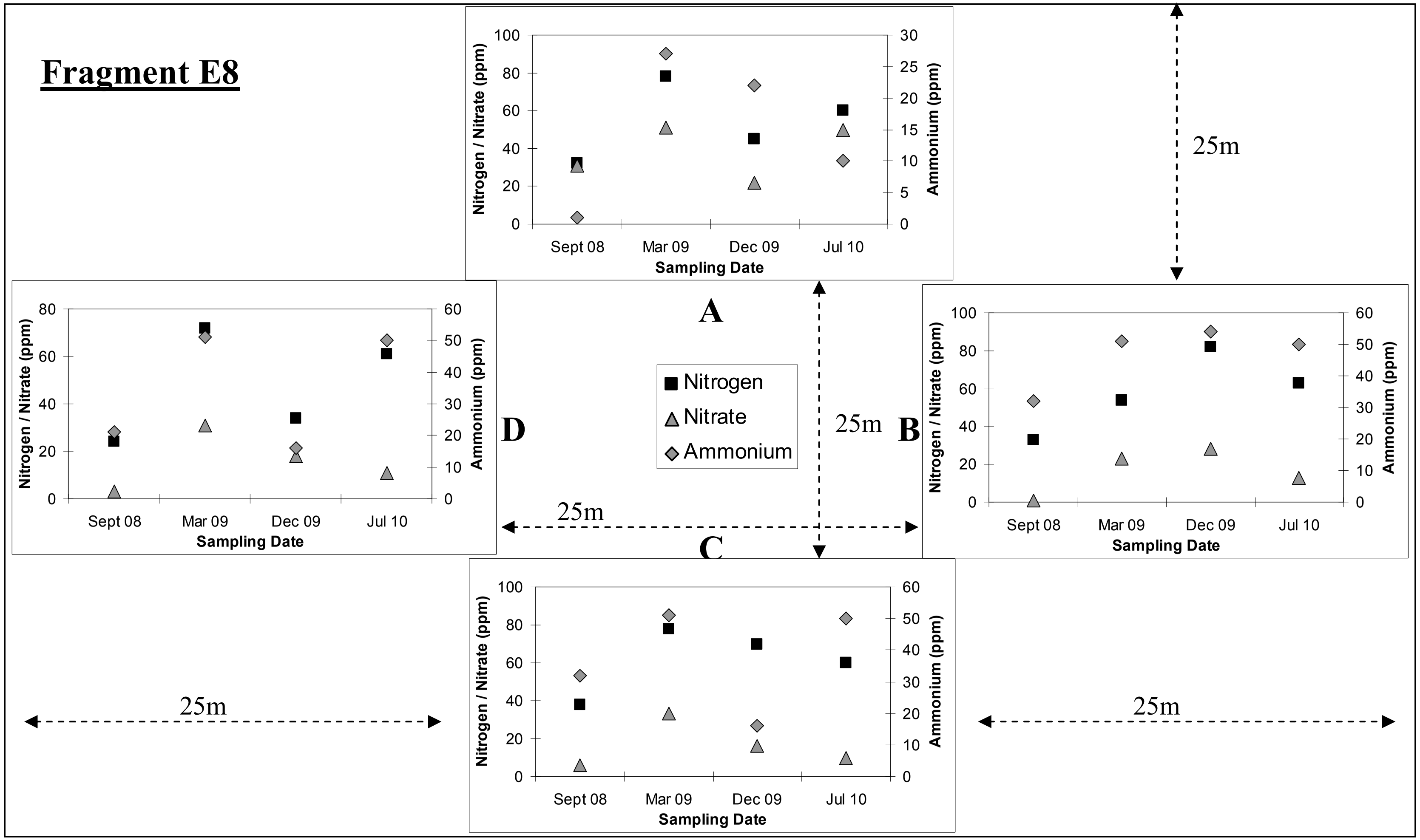

Figure A.1: Extractable nitrogen, nitrate and ammonium results for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10) in grassland fragment E8. Distances of sampling points from fragment edges and from each other are indicated. (Df = 3, no significant within-site differences).

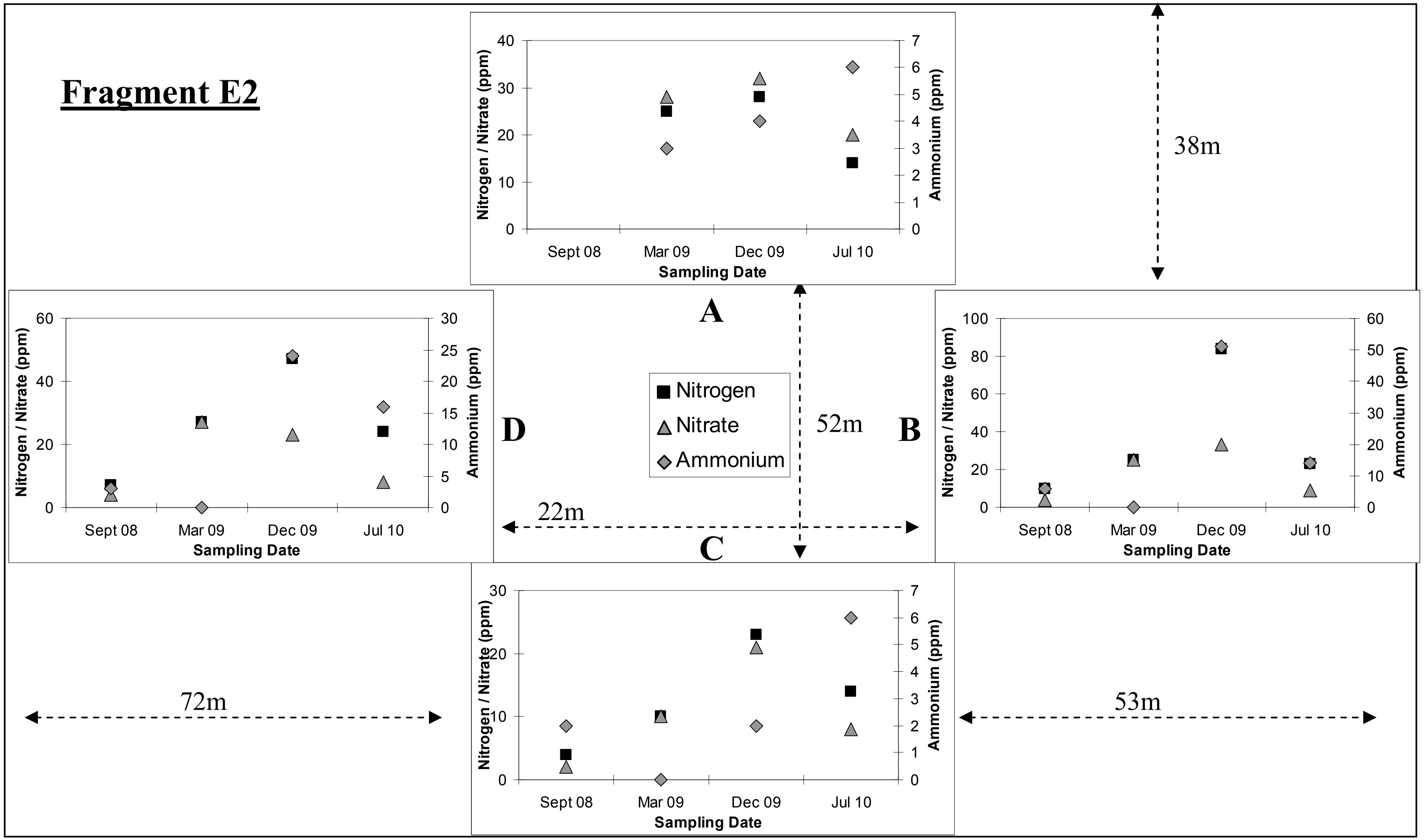

Figure A.2: Extractable nitrogen, nitrate and ammonium results for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10) in grassland fragment E2. The sample for point A in September 2008 was misplaced whilst in transit to the Laboratory. Distances of sampling points from fragment edges and from each other are indicated. (Df = 3, no significant within-site differences).

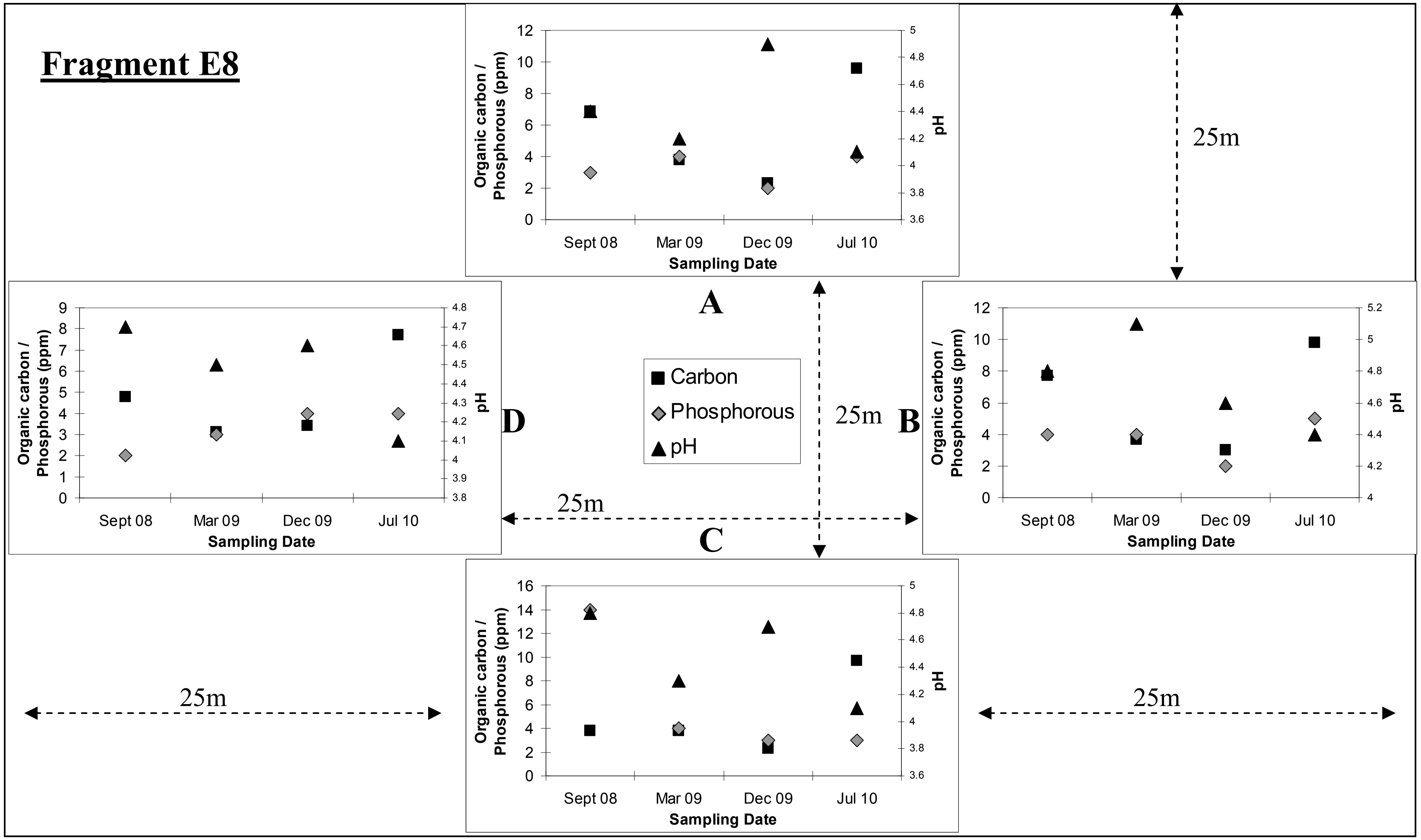

Figure A.3: Organic carbon, phosphorous and pH results for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10) in grassland fragment E8. Distances of sampling points from fragment edges and from each other are indicated. . (Df = 3, no significant within-site differences).

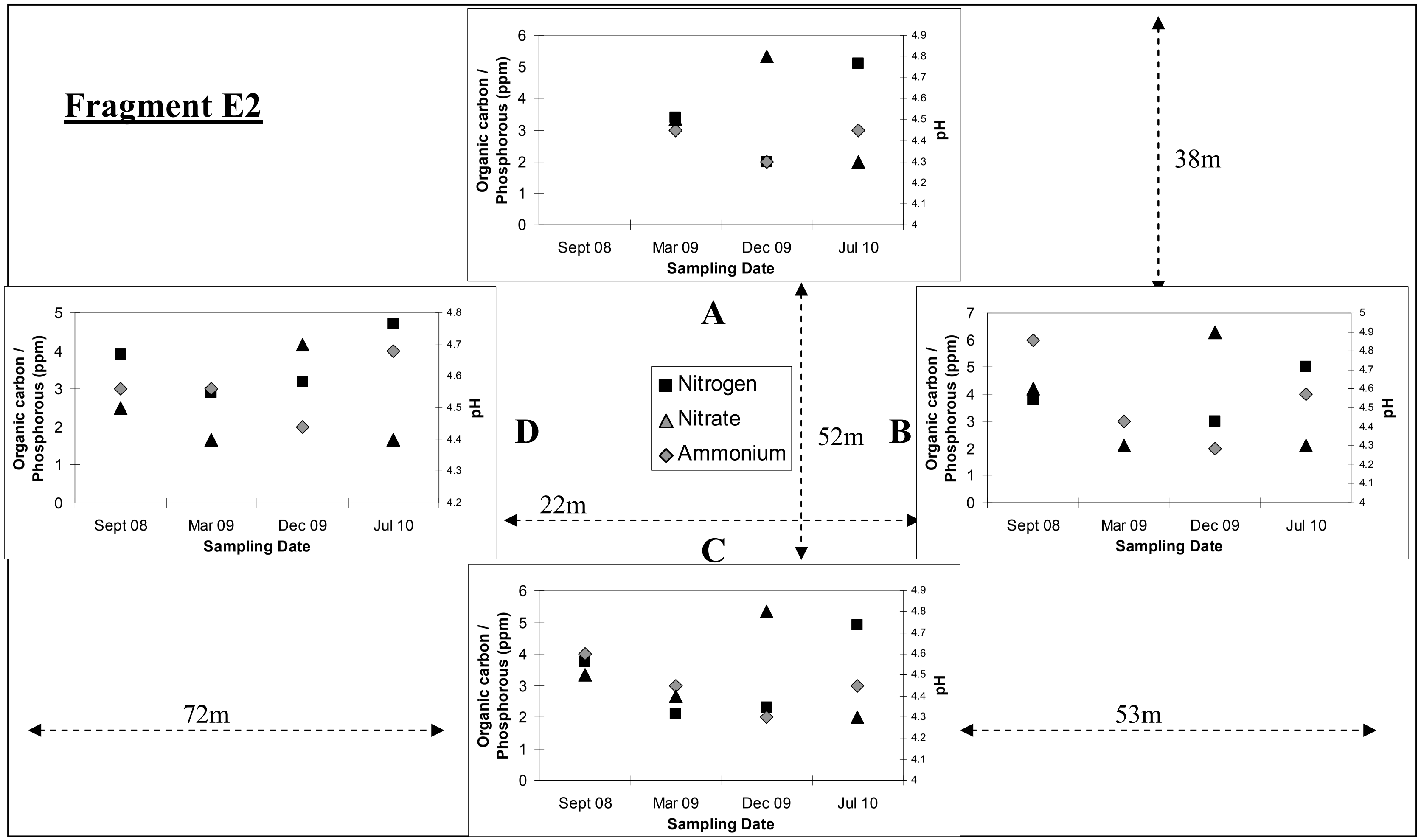

Figure A.4: Extractable nitrogen, nitrate and ammonium results for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10) in grassland fragment E2. The sample for point A in September 2008 was misplaced whilst in transit to the Laboratory. Distances of sampling points from fragment edges and from each other are indicated. (Df = 3, no significant within-site differences).

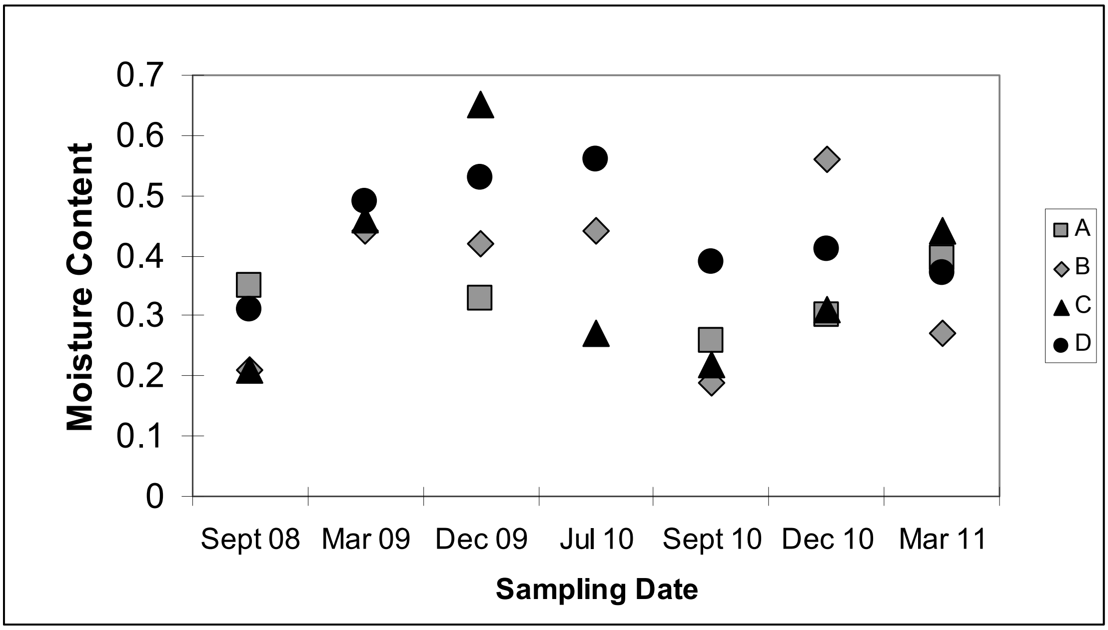

Figure A.5: Moisture content for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10, Sept 10, Dec 10, Mar 11) in grassland fragment E8. The results for point A in July 2010 and March 2009 were outliers and therefore discarded. (Df = 3, no significant within-site differences).

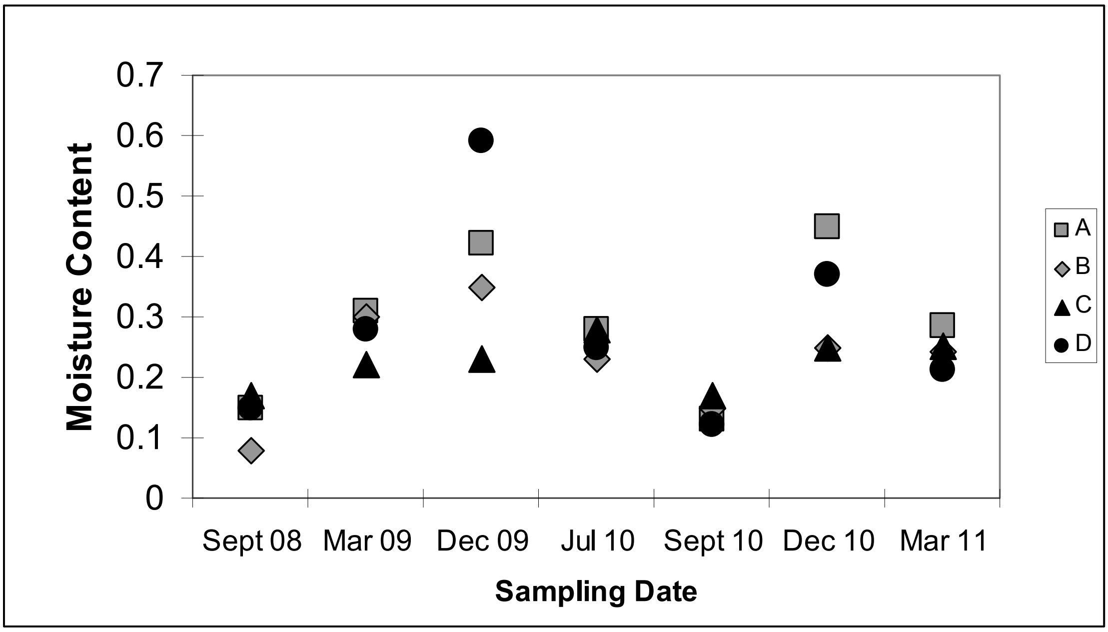

Figure A.6: Moisture content for each sample point (A,B,C,D) and each sampling date (Sept 08, Mar 09, Dec 09, Jul 10, Sept 10, Dec 10, Mar 11) in grassland fragment E2. (Df = 3, no significant within-site differences).

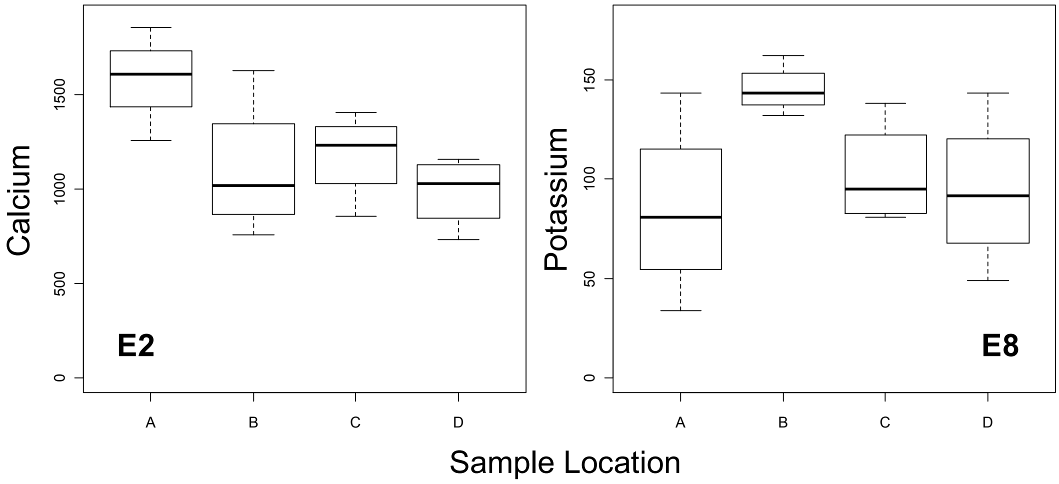

Figure A.7: Box and whisker plots for Calcium values in grassland fragment E2 (left) and Potassium values in grassland fragment E8