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ASPECTS OF A POPLAR-PASTURE SYSTEM RELATED TO PASTURE PRODUCTION IN NEW ZEALAND

A thesis presented in partial fulfilment of the requirements for
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AURELIO GUEVARA-ESCOBAR
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ABSTRACT

Widely spaced poplars (*Populus deltoides*, <100 stems/ha) are the best technology to control soil erosion over 3.7×10^6 ha in New Zealand on sedimentary hill soils. To date, the effects of poplars on water, soil and pasture relations are poorly studied. This thesis compared traditional stable open pasture (OP) and widely spaced poplars (5-40 years old) and its grass/legume understorey (PP) based on rainfall partitioning, soil and pasture characteristics.

It was concluded that mature PP (>29 years old and 37-40 stems/ha) used more water during November (18 days) as evapotranspiration (*ET*, 2.7-3.0 mm d^{-1}) than the OP (2.2 mm d^{-1}). Canopy rainfall interception (1.37 mm d^{-1}) was more important than tree transpiration (0.92 mm d^{-1}) or understorey *ET* (0.4-0.6 mm d^{-1}). Despite the differences in water partitioning, soil water (θ) in the PP was similar or higher than in the OP.

The mature PP had lower topsoil θ (0-150 mm) than the OP during 1996 (37 and 43 %v/v, respectively). PP topsoil was drier in January, May and June, but θ was similar to the OP in other months of 1996. During dry weather (1997), θ in the topsoil was higher in the PP than in the OP. Variation in θ around the trees was significant but small in magnitude. PP soil temperature was lower than in OP particularly during summer.

Soil pH was higher (0.5-1.2 units) in the PP as were exchangeable cations. Poplar leaf litter decomposition along with poplar N nutrition, reduced soil water leaching and legume N-fixation, all contributed to higher soil pH. Using the legume dry matter (DM) as a proxy of N-fixation, the PP fixed 54% of that in the OP. With the exception of lower total N in the PP, little differences were found in organic C, total N, P or S, or soil P or S fertility, hydraulic conductivity, porosity and water aggregate stability between the OP and PP. Earthworm populations were similar or lower in the PP.

Pasture DM accumulation in the mature PP was 60% (6.2 t ha^{-1} yr^{-1}) of that in OP as the poplar canopy (70% canopy closure ratio) allowed only 20% of the photosynthetically active radiation in the OP to reach the understorey. The legume proportion was similar between the OP and PP, although actual yield was lower in the PP. The PP area had slightly lower grass percentage at the expense of higher comminuted tree debris material. OP forage generally had higher feed value in terms of crude protein, metabolisable energy and *in vitro* DM digestibility.

With the exception of higher soil pH, no difference in other soil or understorey characteristics was found between the OP and PP planted with young poplars.

The understorey could take advantage of improved soil water and pH conditions if silvicultural management reduced the shading effect from poplars without impairing soil conservation. Canopy and understorey management options to increase/better utilise pasture DM are discussed.

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GLOSSARY AND ABREVIATIONS[1]

A.C.: after Christ.

ADF: acid detergent fibre.

Agroforestry: refers to silvopastoral systems oriented to timber production or soil erosion control. In New Zealand, sometimes used synonymously with "farm forestry" (i.e., forestry as practised by farmers) or even "any forestry on ex-farm sites". Some users apply the term only to low tree stockings. Here taken to mean the intensive management of trees, pasture, and livestock on the same area of land at the same time. As a stand matures, the pasture and livestock component may become of lesser importance.

Amenity value: means those natural or physical qualities and characteristics of an area that contribute to people's appreciation of its pleasantness, aesthetic coherence, and cultural and recreational attributes.

ANOVA: analysis of variance.

ASC: anion storage capacity.

asl: above sea level.

B.C.: before Christ.

BD: soil bulk density.

Biofuel: plant biomass that is used to generate energy or synthetic petrol (gasoline) not derived from petroleum.

Blanket forestry: plantation of whole farm with a single species, in New Zealand this means *Pinus radiata.*

Block forestry: as in blanket forestry, but only selected areas of the farm are planted.

Breast height: in New Zealand, breast height is taken to be 1.4 m above ground on the uphill side of the tree. Many other countries, including Australia, use 1.3 m.

Canopy: the part of a tree consisting of branches and foliage. "Canopy closure" is the stand age when the branches touch, or nearly so, thereby restricting light to the forest floor.

CCR: canopy closure ratio, the percentage of canopy closure.

Clearfelling: the felling of all trees in a stand at the same time.

Clearwood: wood free of knots achieved through pruning. Tree trunks do not stretch as they grow: they expand only in diameter at any given point. They grow from cells formed just under the bark, so that branch stubs remain at their original height and become "buried" in later knot-free wood.

Compression wood: abnormal wood formed on the lower side of branches and leaning stems. Generally confers undesirable wood properties.

CP: crude protein.

D: drainage.

DAP: diammonium phosphate.

DBH: tree diameter at breast height over bark.

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[1] Parameter identifiers of equations are not listed because same descriptors were used in the linear and nonlinear models for consistency.

DM: dry matter.

D&D: diagnosis and design.

Earthflow: see mass movement.

ET: evapotranspiration.

Externality: positive or negative unpriced values resulting from human activity.

Greywacke: a sedimentary rock composed of silt or sand particles which have been hardened and cemented.

Gorse: *Ulex europaeus*, one of the most important bushy weeds in New Zealand.

Gullying: erosion of soil or rock by ephemeral streams downcutting through hillslopes, after heavy rain.

Hardwood: the common name for angiosperms, or broadleaves. The expression "hardwood" does not necessarily indicate that the wood is hard (e.g., balsa is a hardwood). Natural tropical forests are predominantly hardwoods, although hardwoods also occur in temperate counties. Temperate hardwoods are often deciduous. Hardwoods usually have flowers and broad leaves.

Heartwood: inner wood (inside the sapwood) no longer transporting water or storing food. It is normally darker in colour than sapwood due to deposits of complex organic compounds.

Hill country: all the land with slopes between 12 and 28°, but low relief; typically 100 to 300 metres' difference in elevation. Valley bottoms are usually narrow.

I: tree canopy interception.

IVD: *in vitro* digestibility.

Lopping: cutting one or more branches of a woody plant.

LSD: least significant difference.

LW: live weight.

Mass movement: erosion of soil or rock by gravity-induced collapse. Usually triggered by groundwater pressure after heavy rain, but can also have other causes, notably streams undercutting the base of a slope, or earthquakes. Movement can either be rapid and near-instantaneous (landslides, avalanches, debris flows) or slow and intermittent (earthflows, slumps).

ME: Metabolisable energy.

Mudstone: a sedimentary rock composed of silt and clay particles, compacted and weakly cemented together by a small quantity of lime.

na: not analysed.

NDF: neutral detergent fibre.

NIRS: near infrared reflectance spectroscopy.

Open pasture: hill country pastureland were trees were far away.

OP: see open pasture.

P: rainfall precipitation.

PA: pasture accumulation.

PAR: photosynthetically active radiation.

Poplar-pasture: hill country pastureland widely space planted with poplars.

PP: see poplar-pasture.

Possum: synonym of opposum, a small tree-dwelling marsupial feeding mainly on plant material. Endangered in Australia, but along with rabbits it is the number one pest in New Zealand.

Q: tree sap flow.

Q_c: tree sap flow per unit of projected crown area.

Reversion: spread of indigenous scrub across land after retirement of a land area by fencing and allowing natural succession to occur. Reversion also occurs when fertiliser and grazing management are insufficient.

Rust: poplar leaf diseases (*Melampsora spp.*).

RMA: Resource Management Act, enacted in 1991 in accordance to OECD countries and Uruguay Round agreements on the environment and development.

SAS: Statistical Analysis System.

Sandstone: a sedimentary rock composed of sand grains, compacted and weakly cemented by a small quantity of lime.

Sapwood: the outer and generally lighter coloured and less-durable wood which transports water and stores food (generally starch). It may represent 2-20 growth rings.

Sawlog: A log suitable in size and quality for the manufacture of sawn timber.

SEM: pooled standard error of the mean.

Shelterbelt: A long narrow strip of trees and/or shrubs intended to reduce wind flow, often for agricultural gain. Timber may be a by-product of shelterbelts.

Silviculture: the procedures used in growing trees, especially pruning and thinning.

Softwood: gymnosperms (conifers). The wood is structurally distinct from that of hardwoods (angiosperms) and may or may not be relatively soft physically.

Soil water balance: measurement of soil water content during a certain period while determining inputs and outputs.

SSS: soluble sugar and starch.

STGA: single tree gap area.

Stocking: the number of live trees per hectare, also denominated as "tree density".

SU: sheep unit.

T: tree transpiration.

Tephra: loose material, e.g., ash and pumice, deposited by volcanic eruptions; mantles extensive areas of the central North Island.

TCE: trichloroethylene.

TDM: total dry matter.

TDR: time domain reflectometry.

Tension wood: also denominated compression wood. Abnormal wood formed on the lower side of branches and leaning stems. Generally confers undesirable wood properties.

Th: Throughfall.

Thinning: the removal of trees within a stand at some time before clearfelling. If trees are left lying in the forest, it is "waste thinning" or "thinning to waste". If trees are extracted, it is "production thinning".

Topdress: aerial application seed or fertiliser to pasture or forestland. Land-base applications are generally termed as broadcast application.

TNC: total nonstructural carbohydrates.

TSP: triple super phospahate.

UPA: understorey pasture acumulation.

Veneer: a thin sheet of wood produced by slicing or rotary peeling a log. Used for decoration on a cheaper substrate such as chipboard, or for making plywood.

v_c: sap flow velocity.

v_h: heat pulse velocity.

Widely space planting: low-density tree plantation looking after strategic planting of trees according to the eroded or erosion prone landscape.

α: statistical significance.

θ: soil water content.

ψ: hydraulic conductivity.

$\Delta\theta$: change in water stored within the soil stratum.

Ω: Omega factor, represents the dependence of transpiration on canopy conductance of climatic variables.

$\varnothing$: diameter.

1. Introduction

New Zealand livestock production traditionally depends on grazing and about 5.5×10^6 ha or 40% occurs in hill country (NZMAF 1997a). These pastures are characterised by variable annual production due to climate variation, soils and fertiliser inputs. Soil erosion, due to extreme climatic changes or mismanagement (Grant 1989, Clough & Hicks 1992 1993, De Rose et al. 1993), results in shortfalls in feed supply, loss of resources from the ecosystem and a slow decline in pasture productivity (Douglas et al. 1986, Fahey & Rowe 1992). Increased capital expenditure will also be incurred if control measures are delayed (Grey 1996). Of the total pastoral and arable land 4.5×10^6 ha is susceptible to erosion and requires modifications to current use to reduce soil erosion and achieve an acceptable level of sustainable land use (Eyles 1993). Planting trees can ameliorate soil erosion (Young 1997), and in New Zealand, this is the preferred erosion control tool (Hicks 1995). Farm operations have a wide range of potential tree planting alternatives (Douglas 1992, Fairweather 1992). The appropriate tree planting for any circumstance depends on prospective revenue, cash flow requirements and product (or risk) diversification needs (Chen 1993, Mclaren 1993). In this context, multipurpose trees that control erosion, provide forage during drought and timber income would be advantageous (Benge 1987, Cameron et al. 1991).

Trees act as a soil conservation tool by reducing effective rainfall, through mechanical reinforcement of the soil and the removal of excess soil water (Garrity 1996). In New Zealand, *Pinus radiata*, *Populus* and *Salix spp.* have been used extensively in erosion control (Fransen & Brownlie 1995). *P. radiata* has mainly been used as block or blanket forestry (Maclaren 1993), and *Populus* and *Salix* as wide spaced trees and small blocks (Hicks 1995, NZMF 1995). A contributing factor to the lower utilisation of *Populus* was the arrival of poplar rust during the 1970's (van Kraayenoord 1993). However, new high yield rust-resistant clones (Wilkinson 1996) have the potential to reinstate *Populus* hybrids as multipurpose trees in New Zealand (Eyles 1993).

The integration of woody and herbaceous perennials in agroforestry systems requires good resource use knowledge to implement adequate management and decrease competition between species (Ong et al. 1996). Understanding the components of any system is essential before initiating large-scale or complex studies of that system (Nair 1993). To date, the influence of wide spaced poplars on understorey microclimate, soil properties, and pasture production and forage quality have not been studied under New Zealand hill country conditions.

Work on the effects of agroforest tree planting on soil and pasture properties under widely spaced trees has been largely restricted to *P. radiata* (Hawke & Knowles 1997). There is some information regarding the mechanisms involving poplar root systems in erosion control (Hathaway 1973), but little is known about the effect of poplars on soil properties. There is also scarce information on the effects of poplar on water use (NWSCO 1983 1987) or on pasture production (Gilchrist et al.

1993). No information is available on the effects of poplars on pasture feed quality. There is evidence to suggest that poplars are very competitive for water or nutrients (Bowersox & Ward 1977).

1.1 Objectives and site selection

This thesis project was designed to investigate pasture characteristics, water relations and soil properties in widely space-planted poplars to control soil erosion. This was compared with a traditional open pasture land-use. The poplar-pasture system had three interacting components: the woody perennial represented by mature *P. deltoides*; the perennial pasture mixed grass/legume understorey characterised by low fertility pasture species; and the grazing animal component, namely beef cattle and sheep. Measurements were obtained from the poplar overstorey, the pasture understorey and the physical environment under the poplar canopy and the open pasture. Although the animal component plays an important role, its examination was beyond the scope of the present research. However, the influence of the animal component in the system is briefly discussed based on the farm owner's experiences and observations taken during the study.

Research in the thesis focussed on gaining a better understanding of the influence of mature trees when grown as wide spaced planted poplars for soil conservation on hill pasture, on water relations, soil characteristics and pasture characteristics. Rooting systems was not part of the investigation, it is only reviewed in Chapter Two, and the work on tree root systems by several authors is used to support the development of different aspects of pasture production and water relations in Chapters Three, Four and Five.

Most of the research was based on a mature system (>29 years), to ensure any tree pasture effect were clearly measurable. A hill in a commercial farm in the Pohangina Valley (Pohangina Hill 1, Figure 1.1) was selected as the main site for this project. The site belongs to a catchment with lithologies and physiography susceptible to massive soil erosion (Appendix I). The site was representative of widely spaced poplar plantings used extensively for soil conservation in the North Island of New Zealand. The poplar stand had physical attributes and relatively

Figure 1.1. View of the commercial farm in the Pohangina Valley, New Zealand from the east road on August 24, 1996. The numbers denote the main site, Pohangina Hill 1 and the secondary site Pohangina Hill 2 poplar-pasture systems used in the study.

Figure 1.2. View of Pohangina Hill 1 poplar-pasture system on November 17, 1996.

homogeneous conditions that limited stand edge effects (Figure 1.2). Secondary sites with either, young or mature poplars were used in the second year of the study. One site was located on the same farm in the Pohangina Valley (Pohangina Hill 2). Another site was selected in the Rongoiti area (Rongoiti) representing typical New Zealand hill country. Measurements also took place at a site recently planted (5 years) in poplars at the AgResearch's Ballantrae Hill Country Research Station to determine if observed differences in the mature poplar pasture system where also found in a site with younger trees (Ballantrae, Figure 1.3).

Figure 1.3. View of the Ballantrae poplar-pasture system on November, 1997.

At all sites, poplars had been planted to control or prevent further soil erosion. All determinations were based on the comparison of poplar characteristics or conditions under the poplar canopy and adjacent stable hill open pasture, hereafter denominated the 'poplar-pasture' and 'open-pasture' areas.

Specific objectives of the thesis were to:

(1) determine the rainfall partitioning in poplar-pasture association and compare it with a traditional pasture system for 18 mid-spring days in grazed areas of a hill environment.

(2) determine the impact of poplars in a poplar-pasture system on hill soils and compare it with stable non eroded hill pasture soils.

(3) evaluate the influence of poplars on pasture characteristics and compare it with the open pasture system. Environmental factors, namely light, soil, water, and temperature, were measured to determine how the trees modified the understorey environment.

(4) determine poplar leaf litter production, feed quality and the effect on germination and early growth of pasture species.

The Pohangina Hill 1 site was the main site used to obtain data for comparison of the poplar-pasture and open pasture systems. Conclusions obtained at Pohangina Hill 1 were tested at other secondary sites to develop a conceptual model of the poplar-pasture system with wider application. However, time, budget and instrumentation constraints also decided the extent and aspects explored in the secondary sites. Two glasshouse experiments helped to determine the effects of poplars on seed germination and early growth of improved pasture species.

1.2 Thesis organisation

This thesis is divided into six chapters. Following the introductory chapter, the most important factors surrounding the interpretation of the role of tree on soil conservation are reviewed in Chapter Two. Chapters Three to Five present the three aspects of the poplar-pasture system researched and information from the different sites and studies are integrated accordingly. The rainfall partition in a poplar-pasture and the open pasture is presented in Chapter Three. The soil fertility and biophysical aspects of the poplar-pasture and open pasture systems are examined in Chapter Four. The corresponding microclimate, pasture accumulation and pasture feed quality of the poplar-pasture and open pasture systems are presented in Chapter Five. The relations with microclimate, soil fertility, plant community species and feed quality are also explored. A summary of the findings and a presentation of possible management options for the poplar-pasture system is made in Chapter Six. Chapters Three to Five are presented as scientific papers but in thesis format. Except for Chapter One where the references are merged into those in Chapter Two and placed at the end of Chapter Two, the references relevant to individual chapters are at the end of each chapter. With the exception of Chapter One, all chapters have a table of contents at the beginning of the chapter. Important lithologies related to the Pohangina Valley sites are presented in Appendix I. Pohangina Hill 1 soil profile descriptions are shown in Appendix II. The code to simultaneously model sap velocity at four depths is presented in Appendix III. Pasture mineral content at different sampling dates at Pohangina Hill 1 site is presented in Appendix IV. Hypothetical feed budgets for the Pohangina Hill 1 site are presented in Appendix V. The publications derived from the thesis work are listed in Appendix VI. The biography of the author is summarised in Appendix VII.

2. Review of literature

2.1 Introduction

The New Zealand Resource Management Act (RMA) aims to ensure that use, development and protection of natural and physical resources enables people to meet their present needs without compromising the ability of future generations to meet their own needs (RMA 1991). Within the framework of the RMA, land users have to demonstrate their farming practices do not have a deleterious impact on resource condition (NZME 1995). However, in some areas of the country, erosive processes have undermined the resource base (Adams 1995, Clough & Hicks 1992, Clough & Hicks 1993). Since the 1940's, many techniques have been used in erosion control on pastoral land (Hicks 1995), but most emphasis was placed on tree planting, largely *Populus* and *Salix* species (NWSCA 1985). Tree planting is highly regarded as a sustainable practice with enormous mitigation properties and its use is widely encouraged (McKenzie 1996). However, trees interact with other components of agricultural ecosystems through a variety of mechanisms, some of them, poorly understood and researched (Ong 1996). Understanding the components of any system is essential before initiating large-scale or complex studies of that system (Nair 1993).

In this chapter, trees, pasture, animals and soil and its erosion process are reviewed as components of the pastoral production system in New Zealand. The following sections provide a conceptual framework for the analysis of the effects of mature poplar trees on pasture production and soil characteristics.

Section 2.2 reviews current knowledge on poplar characteristics and tree-pasture associations. Particular emphasis is on the benefits obtained in relation to erosion prone landscapes.

Section 2.3 reviews the role of trees as a soil conservation option, focussing on the root system and the tree capacity to reduce soil water as mechanisms of land stability.

Section 2.4 reviews the characteristics of the New Zealand hill country, its relation to erosion problems and the importance of soil erosion control in ecosystem sustainability.

2.2 Poplar experience in New Zealand and abroad

Silvopastoralism is an old practice in Europe (Braziotis & Papanastasis 1995), but it was not until 1969 that this form of agroforestry was formally considered in New Zealand (Hawke & Knowles 1997). During the last decades agroforestry has had more relevance, as an integrated land use approach, in the tropics than in the temperate zone (Nair 1993). In New Zealand, most of the silvopastoral research has been based on *Pinus radiata* (Maclaren 1993), whereas the term agroforestry usually refers to woodlot blocks, trees-on-pasture and forest grazing (Mead 1995). However, in an internationally broad scale definition, these variations are known as particular agroforestry systems (Nair 1985).

The predominant soil conservation method in New Zealand is the planting of trees to prevent soil erosion (van Kraayenoord & Hathaway 1986). *P. radiata* is the preferred forestry species, but *Populus* and *Salix* also are commonly planted in silvopastoral arrangements (Stace 1996). Although initially based on European experience where traditionally poplars were cropped as fast growing trees in lowlands (FAO 1959, FAO 1979, FAO 1997), in New Zealand they were used as a land conservation tool since the European settlement (van Kraayenoord 1993). New Zealand is probably the one of the few places in the world where poplars are planted on hillsides (Wilkinson 1993). The poplar incorporation into silvopastoral systems has been as successful when well implemented (Hicks 1995, NZMAF 1997c) as many other conservation technologies developed over the last half century (Hurni et al. 1997). Some farmers have been able to manage and improve their land resource with regional conservation assistance (Douglas 1992, NZMAF 1997a). However, most of this experience has focused on resolving the practical aspects of the implementation (van Kraayenoord & Hathaway 1986), and the impact of poplar trees on the environment is little researched (Wall et al. 1997).

2.2.1 The poplar species

Poplars are deciduous hardwood trees of the genus *Populus* in the willow family, *Salicaceae* (Viart & Fugallil 1993). The genus has a diversity of species that readily hybridises (PMNN 1993a). Poplars have separate male and female flowers borne on separate trees (Bean 1977). The flowers are small and closely packed into soft, tassel-like clusters called catkins (Kennedy 1985). *P. deltoides* is one of the most widely planted (FAO 1979) and hybridised species in the genus (PMNN 1993b). The *P. deltoides* fruits are small, flask-shaped capsules containing a number of cottony-tufted seeds (Kennedy 1985). The flowers are wind-pollinated, and wind or water disperses the seeds (Holifield 1989).

Poplars are widely distributed throughout the temperate region of the Northern Hemisphere (van Kraayenoord, 1993). These fast-growing trees are native to Europe and North America and

China (Reid & Wilson 1985, Ou et al. 1997). They are amongst the easiest of all trees to propagate and grow (Hathaway 1973). For this reason they have been planted extensively as street trees and used for reafforestation (Bean 1977, FAO 1997). They thrive in moist soil and are often found along stream banks (NZPC 1992). They prefer moist valley bottoms and lower hill slopes to exposed upper slopes and ridges (NZMF 1995). With few exceptions (Tschaplinsi et al. 1998), poplars are not drought resistant and require at least moderate soil water throughout the growing season (Miller & Wilkinson 1995). Poplars will grow in low rainfall areas provided they are confined to soils with a high water table, or irrigation (Eyles 1993). Poplars are tolerant of a wide range of soil types, but will grow most rapidly on deep loamy soils (NZPC 1995).

2.2.1.1 Species introduced in New Zealand

The name poplar is applied collectively to more than 35 species in the genus, which include the aspens and cottonwoods (Bean 1977). With the exception of the balsam poplar, *P. balsamifera*, native North American species are denominated aspens or cottonwoods (Kennedy 1985). The Lombardy poplar, *P. nigra* 'Italica', and the cottonwood poplar, *P. deltoides* were first introduced in New Zealand between 1840 and 1850 (Van Kraayenoord, 1993). Originated in North America, cottonwoods may exceed 30 m in height and 1.2 m in trunk diameter (Holifield 1989), in fact, one of the biggest cottonwoods is found in New Zealand (Van Kraayenoord, 1993). The *P. nigra*, native to Eurasia, grows to 27 m tall and has a distinct tall, narrow shape (Kennedy 1985). It was derived from a single tree showing the columnar growth and has been propagated by sprouts, as only male trees usually occur in nature (Holifield 1989). Poplars in New Zealand have been mainly represented by the two above mentioned species and to a lesser extent by *P. alba* and *P. yunnanensis* (Van Kraayenoord, 1993). *P. deltoides* and *P. nigra* have been used mainly for amenity and soil conservation purposes in New Zealand (Miller & Wilkinson 1995). However, *Populus* species have many other uses: as an ornamental, shade tree, windbreak, source of fuel, fibre, lumber, plywood and speciality products, and as an integral component of riparian ecosystems (Beaton 1987, Eyles 1993, Jaswal et al. 1993, Quam 1997a). More recently, it has attained new prominence as a renewable crop on marginal or surplus farmland (PMNN 1993a). The many advantages of reafforestation and plantation management of poplar have reinstated it as a true multipurpose tree (Wilkinson 1993, Carlson 1994).

The arrival of rust diseases (*Melampsora spp.*) to New Zealand in 1973-76 caused high mortality among the planted trees (Reid & Wilson1985), causing planting and conservation schemes to be disrupted by lack of resistant clones (Wilkinson, 1993). Damage was so extensive because only a few clones were widely planted and almost all were susceptible to the disease (Maclaren 1993). Over the last 20 years, new disease and possum-resistant clones have been developed for erosion control, agroforestry, and shelter (Miller & Wilkinson 1995). All new clones (i.e. Yeogi

I, Kawa and Toa) have fast initial growth over the first 3-5 years and after 5-10 years growth is similar to that of *P. radiata* (Wilkinson 1996).

Poplars as well as *Eucalyptus* illustrate the opportunities offered by fast growing tree species when grown in plantations (NZMF 1995). In 1995 there were more than $1x10^6$ ha of poplar plantations in Europe and $1.3x10^6$ ha in China (FAO 1997). Over $6x10^6$ poplar trees have been planted during the last 40 years for soil conservation and windbreaks on New Zealand farms (NZPC 1995). It is estimated that about $3x10^6$ poles are currently in sawlog condition (Wilkinson 1993). In 1984 nearly $1.3x10^6$ rooted trees and poles were planted in New Zealand. However, due to the depressed farm economy and the reduced government spending on soil conservation, this number rapidly declined to $3x10^5$ in 1988 and $1.7x10^5$ in 1992 (van Kraayenoord 1993).

2.2.2 Poplar establishment

Easy vegetative propagation is the principal reason for using poplars and willows (*Salix*) rather than other tree genera for conservation plantings under pastoral land use (Hathaway 1973, PMNN 1993a, Thompson & Luckman 1993). Also important are the high establishment success and the possibility to restart grazing quickly (Sheppard & Lambrechten 1983, Wilkinson 1993) in comparison to *P. radiata* (Gillingham et al. 1976). They are successful because they have a rapid growth, an extensive root development, and tolerance to periodically saturated soils (Miller et al. 1996). The attraction of poplar planting for many farmers is the prospect of combining erosion control and timber production with continued grazing (Reid & Wilson 1985, Fairweather 1992), along with the additional benefits of livestock shade/shelter and fodder source (Benge 1987, Stace 1996, Prebble 1998).

2.2.2.1 Poplar planting

P. deltoides may establish on suitable sites through natural seed-fall, or by cuttings (Holifield 1989). However, poplars do not produce good seed freely in cultivation, and when they do, it will certainly produce hybrid plants unless male and female trees of the same species grow near together (Bean 1977). In New Zealand, there are three kinds of tree stock type for establishment, poles (3 m pole), rooted cuttings (0/1 tree usually 1.5-2.0 m long) and 1m stakes (Evans 1973, van Kraayenoord & Hathaway 1986, Stace 1996). Poles and stakes do not have roots at planting time. The three plant stock types are equally effective, although sensitive to soil water and depth in certain cases (Stace 1996). A cutting is planted at 25-35 cm depth (Evans 1973) and a pole rammed to 1 m (Wardrop 1996). Deep planting is important to ensure permanently moist conditions and to give maximum stability to plants (Beaton 1987).

When poplars are destined for marginal lands with seasonal exposure to moisture shortages rooted material is preferred (Evans 1973). Establishment will be more reliable if rooted planting stock is cut back to a bud at about 0.4 m above ground level (NZPC 1995). This reduces the stem mass in relation to the root system so that a soil water deficit will not result in drought stress and die back (Stace 1996). Under dry conditions *Eucalyptus*, and occasionally wattles (*Acacia*), are increasingly being planted for erosion control (Sheppard & Lambrechten 1983, NZMF 1995, Thorrold et al. 1997). They have similar advantages to poplars, but are more expensive to propagate and do not provide supplementary fodder for livestock (Miller et al. 1996).

2.2.2.2 Poplar silviculture

Land use determines the selection of type of poplar stock, planting density and protection system (Sheppard & Lambrechten 1983, NWSCO 1985). The farmer's motivations and constraints for tree planting also are an important decision-making factor (Fairweather 1992). Figure 2.1 shows a proposed elimination criteria including beliefs about trees, knowledge about forestry and whether trees were already present. Recommended planting density is usually 200-280 sph (stems per hectare) for stakes and 150 sph for poles (NZMF 1995). If pastoral production is a major consideration, a 100 sph or less agroforestry arrangement could be used, but up to 200 sph will be appropriate for timber production (NZPC 1995). Typical planting densities on hillslopes will vary and depend upon the erosion problem to solve (McKee 1973, Hicks 1995). When planning early introduction of livestock the grazing value of pasture should be high and

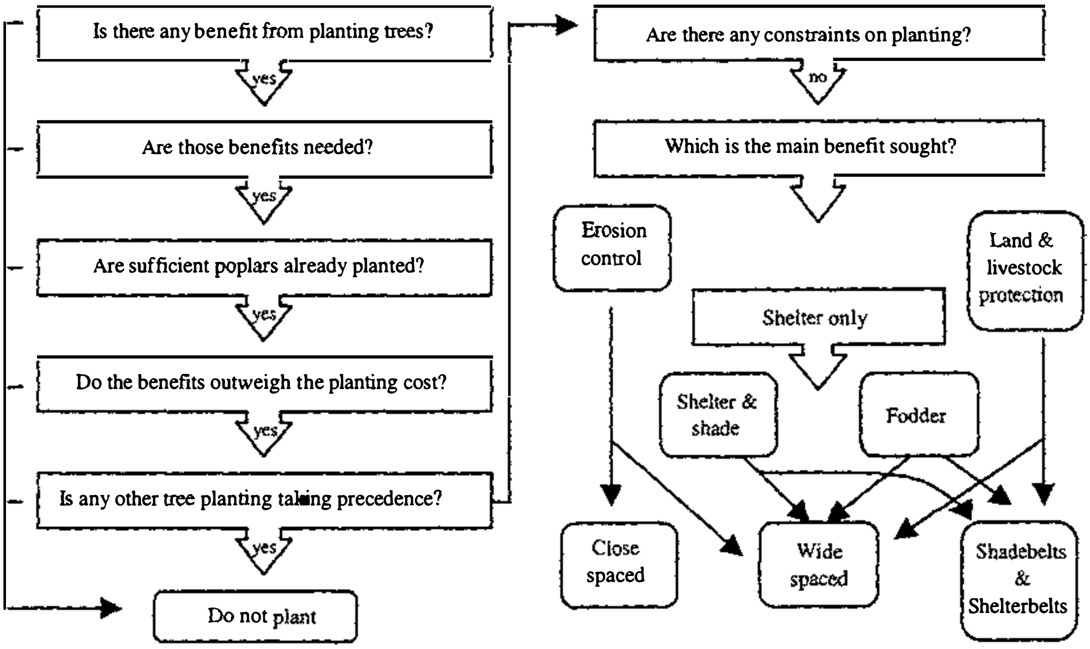


Figure 2.1. Decision making tree incorporating aspects and motivations of New Zealand farmers for planting or not poplars. Modified from: Fairweather (1992).

the risk of erosion when reintroducing animals should be low (Stace 1996). Pole planted areas should be grazed with sheep only, or if protected with plastic sleeves (NZPC 1995), they can be grazed with almost any livestock class (van Kraayenoord 1993, Stace 1996). Unprotected poplar paddocks should be retired from grazing for about three years to allow the trees to grow enough and develop rough bark to resist damage (McKee 1973, NZMF 1995).

Timber grown poplars require intensive care for most of their 15-20 year growing period with regular pruning beginning in year, one depending on growth rate (Beaton 1987, NZMF 1995). Form pruning very young trees improves tree shape and makes pruning easier in later years (Reid & Wilson 1985). A single thinning to reduce the stocking to 100 sph will be needed as canopy closure begins (NZMF 1995). No particular management exists for poplars grown exclusively for land conservation, although it might be desirable to maximise pasture growth.

2.2.3 Poplars primary role: land conservation

Tree planting offers many opportunities for slope stabilisation (Grey 1996). In New Zealand, farmers appear to be aware of the benefits of poplars or willows (Eyles 1993, van Kraayenoord 1993). Although there is a range of attitudes to planting poplars (Cowperthwaite 1994, Fairweather 1992) it is widely accepted that close or spaced plantings of broad-leaved species can reduce soil mass movement as well as when close reafforestation with *P. radiata* or natural scrub reversion is practised (Miller et al. 1996). Poplars, along with other tree species have been identified as an early coloniser of disturbed sites (Lefroy et al. 1992). However, very few studies demonstrate the effect of poplar trees on soil conservation, although 80 years of soil conservation practice, some 30 years of erosion surveys, and some 10 years of geomorphological investigations support poplar usefulness (Miller et al. 1996).

A study by Hicks (1991 unpublished, cited by Miller et al. 1996) demonstrated that well implemented soil conservation tree plantings in pasture reduce fresh mass movement by 60-80%, but change the shape of erosion distributions. Inadequate plantings reduced soil movement only 10-20% (Miller et al. 1996). Adequately planted and tended broad-leaved trees can control shallow gullying as pair planted trees at 2-4 metre spacing (Luckman & Thompson 1991). Earthflows with shallow or no gullies were satisfactorily controlled by spaced planting of willows and poplars at 5-8 metre spacing over at least 60% of the surface. Earthflows with deep gullies were effectively stabilised only where surface plantings were accompanied by gully stabilisation as described above. It was concluded that poplars or willows need to be planted at 8 x 8 m spacing (156 sph) or closer for land stabilisation (Thompson & Luckman 1993). *P. radiata* although very popular in New Zealand, is not the best option when controlling gully erosion (Mclaren 1993, Figure 2.2).

Figure 2.2. Mangatu gully in the Gisborne area, New Zealand. The gully covers an area over 1.5 km^2 and probably was a consequence of forest clearing early this century (N. Trustrum personal communication). Although the site is reforested the gully continues to creep. A bus can be seen on the ridge that separates this gully from another one of similar magnitude.

In another study in the Gisborne area, Hawley & Dymond (1988) examined a group of hill-slopes planted with wide spaced trees after a severe rainstorm. Twenty metre spaced Italian poplars (*Populus x euramericana*) with a 66% establishment rate were studied for their ability to reduce landslips around them. Landslide scars tended to occupy areas away from the trees. This influence decreased with distance from the trees, becoming undetectable at a radius of 11 m. The storm caused 20.9 % of the study area to become immediately unproductive for pasture growth, either through landsliding or deposition of debris. It was estimated that the trees reduced storm damage by 13.8 %. If the trees had been planted on a 10-m spacing, with a 100% establishment rate, storm damage could be reduced by at least 70% according to a model developed.

2.2.4 Poplars secondary role: timber

P. deltoides is a diffuse-porous hardwood; the annual rings are not conspicuous, but can be distinguished (Kennedy 1985). The wood of *P. deltoides* is rather soft, and relatively weak, but its strength-to-weight ratio is high (Holifield 1989). It is moderately light in weight, 400-440 kg m^3 at 12% moisture content (Kennedy 1985, NZMF 1995). Poplars have a wood density similar to that of other fast growing trees and many properties are similar to *Compressus lusitanica* or *Sequoia sempervirens* (Miller & Wilkinson 1995). Poplar, *P. radiata*, and fast growing *Eucalyptus* are basically trees of similar physical dimensions but poplars have a narrower range of natural adaptations in New Zealand (NZPC 1995). A disadvantage associated with *P. deltoides* is the frequent presence of gelatinous fibres in what is known as "tension wood" (Kennedy 1985). Tension wood is minimised by growing poplars at uniform spacing on sites not exposed to the worst of prevailing winds. Tension wood is not only associated with poplars, it can develop in *Eucalyptus* and *P. radiata* when grown on exposed sites (Phillips & Watson 1994).

Primary wood products include biofuel, matches, toothpicks, lumber, veneer, plywood, particle-board, fibreboard, and pulpwood (NAC 1997a). Poplar is mainly used in the Northern Hemisphere for pulpwood (FAO 1979). Fast growing poplar trees are prized for paper production because their lignin is weaker than in other trees and less costly to break down (Wardrop 1993). Finished wood products include pallets and crates for food storage (Holifield 1989). Biofuel and pulp production are the reasons why poplars have been hybridised and cultivated to produce more biomass annually than any other hardwood or conifer tree in the United States (Hall 1997, NAC 1997a).

Production rotations of *P. deltoides* vary according to end products, 2-5 years for fibre production, 6-15 years for bolt wood, and 15-30 years for lumber and veneer logs (Kennedy 1985, Wilson & Reid 1985). Poplar clones have a similar productivity to *P. radiata* if properly matched to site and pruned on a similar schedule (NZPC 1995). About 200-250 m^3 ha of sawlog production at around 15-18 years could be expected for a crop established at a final spacing of 100 sph (NZPC 1995), 300 m^3 ha at 140 sph in year 15 (Wester 1994). At a stocking rate of 200 sph and a rotation of about 20 years, a yield of 400 m^3 ha could be expected (NZPC 1995). There is a growing realisation that poplars when pruned regularly can produce a valuable timber crop (Cowperthwaite 1994, Silvester 1994, Wester 1994, Wardrop 1996, Wills 1997b). Timber returns from the older hybrid poplars (unpruned) are currently equivalent to *P. radiata* boxing grade or grade “A” on the New Zealand market (Wester 1994). The return for clearwood pruned logs of newer hybrids should exceed this, as they are more suitable for uses such as veneering (Wills 1997a). The current lack of a reliable supply of defect-free poplar logs has been an impediment to market development (NZFM 1996).

2.2.5 Integrating trees into farms: Agroforestry

Agroforestry, in its broadest definition, provides possibilities for reintroducing trees onto virtually any class of land (Nair 1985). Farm forestry or agroforestry designs have been promoted by those interested in the joint production of forestry and agricultural products and environment protection (Pearse 1995). In New Zealand, farm forestry has developed considering the use of multipurpose tree species (Hawke & Knowles 1997). Individual farmers had employed a combination of agroforestry practices and often had been innovative in their approach (Brann & Brann 1988, Mead 1995). A variety of designs have been attempted to match a given land use (Mead 1995), rather than promote "favourite" or "pet" agroforestry technologies (Reid 1996). In most cases, reclamation agroforestry has achieved successes by means of sound field applications (Wall et al. 1997) rather than specifically from research (Young 1997).

Farm forestry or agroforestry, rather than being distinct types of plantations or management options, should be seen as an approach to plantation design and development (Young 1997). In its most basic and robust form, diagnosis and design (D&D) embodies a common-sense problem solving approach (Buck 1995). The result is an approach that is similar to whole farm planning in that the emphasis is on design of a system for a given paddock, farm or catchment rather than the promotion of a particular land use option (Campbell 1990). Once land management systems are reviewed, and problems and opportunities are recognised, the role that trees must play if they are to solve the problem can be identified (Prinsley 1992, Fairweather 1992). Where multiple objectives are identified criteria common to each are highlighted as are those which may initially appear contradictory (Reid 1996).

Putting trees back on all types of degraded land is not always the best decision when factors such as the economics, social and ecological sustainability are considered (Stomph et al. 1994). The case of the North Auckland region of New Zealand was examined along with another from the Western Ghats region of India (Hunter et al. 1995). The New Zealand example shows that both the direct and maintenance costs of reafforesting degraded land can be greater than reforesting better land. The Indian example demonstrates that land which appears to be degraded might, in fact, be important to someone's livelihood and the political support for reafforestation can be lost unless that implicit right is recognised.

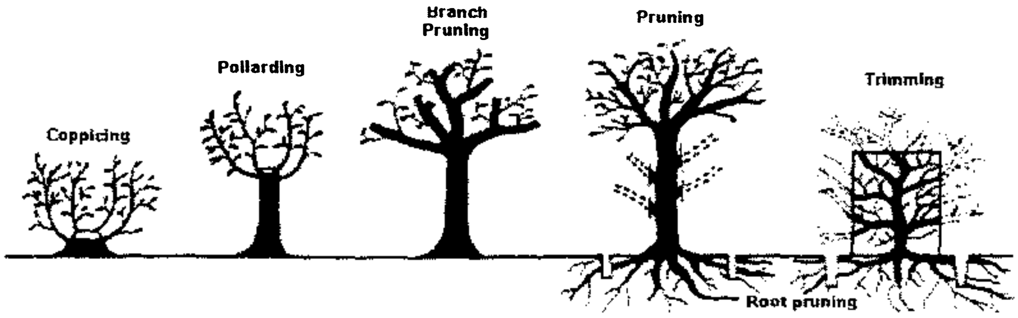
2.2.6 Silvopastoralism: grazing opportunities.

Traditional pastoral farming on much of New Zealand's hill country is considered unsustainable (Eyles and Newsome 1992, Hicks 1995, Lambert et al. 1996). The erosion of topsoil and leaching is reducing the productivity of the land (NZMAF 1993), and lowering the quality of stream water to unacceptable levels (O'Loughlin et al. 1984, Wilcock 1986). While some hill country farms have been converted into forest plantations (NZMF 1996), some farmers prefer to continue within the livestock industry, but want to increase the stability of the land they manage and the quality of the streams running off their farms (NZMAF 1992, Stomph et al. 1994). Planting trees in areas that are too erosion-prone to allow grazing can achieve these objectives (NWSCA 1987, Maclaren 1995). Trees can be arranged on the landscape so they protect steep hill slopes and streamside zones by providing cover from heavy rainfall and improving the infiltration capacity of the soil (Fahey & Rowe 1992, Garret & Buck 1997). In addition, it is likely there will be a long-term increase in the overall productivity of the land, even if land is taken out of agricultural production and converted to trees (Hawke & Maclaren 1990, Olson et al. 1993). Since most New Zealand farmers perceive sustainability as economic sustainability (Blunden et al. 1996) the potential economic benefits from agroforestry are appealing. Poplar trees are able to maintain pasture growth at about the same level as on unstable, unplanted hillsides, that is provided tree plantings are restricted to the areas that are actually unstable, greater stability is achieved with little or no net loss of pasture production (Miller et al. 1996). However, *P. deltoides* agroforestry may have downsides, for example, stuck *P. deltoides* fruits on grass have been associated with decreased pasture intake (Angus Gordon personal communication).

2.2.7 Poplar agroforestry

Poplars have evolved as a technology promoted primarily for land conservation, with the multipurpose nature of the species emanating accordingly to the farmer's needs (Trustrum & Blaschke 1992, van Kraayenoord 1993, Hicks 1995). Management flexibility is perhaps the most important quality of poplars as a multipurpose agroforestry tree species (Lefroy et al. 1992, Newman 1997). Silvopastoral systems generally involve the close interaction of trees with crops (i.e. alley cropping) or livestock (Nair 1985). There are different techniques used to manage trees in these closely integrated systems in order to avoid tree dominance (Figure 2.3) and manage tree and understorey resources (von Carlowitz 1991). Some of these management practices will prevent adequate development of many tree species. On the other hand, poplars are well adapted.

Figure 2.3. Illustration of some of management techniques applied to multipurpose trees (von Carlowitz 1991).



2.2.7.1 Poplar agroforestry overseas

Poplar agroforestry is well developed in a number of countries, including Argentina, Australia, Canada, China, India, Italy and the United States of America (Reid & Wilson 1985, Garrett & Buck 1997). In many countries, the growing of agricultural crops between rows of young poplars has been performed for many years (Dupraz & Newman 1997). In the Po Valley, Italy, the combination of grazing enterprises with poplar growing is managed by putting in forage crops for three or four years until the trees are well developed (FAO 1959). The crops involved are selected from perennial types, whose growth cycle extends over the period when the poplars cause least shade and are dormant, therefore utilising the full potential of the site (Reid & Wilson 1985). Poplar plantations in Europe and eastern Canada have been interplanted with corn, potatoes, soya beans, and other cereal and tuber crops, in different temporal sequences, for the first three to six years after tree establishment (Gold & Hanover 1987 Dupraz & Newman 1997). Many of the poplar plantations are only grown for an additional five to ten years after crop harvest before harvesting and establishment of the next rotation (Beaton 1987). In Australia, various melon and squash crops have been grown for two years, followed by permanent pasture, with cattle grazing on both the pasture and branches lopped from the poplars (Reid & Wilson 1985). Indian poplar agroforestry indicates that shade tolerant species perform better as intercrops than as monoculture (Jaswal et al. 1993). However, poplars may compete more with the intercrop than *Eucalyptus* (Singh et al. 1989). Reductions in yield from the intercrop have been observed even during wintertime for *Avena sativa* (Nandal & Bisla 1995). Root pruning appears to be a prerequisite for acceptable understorey yields (Beaton 1987, Newman 1997).

In the future, integration of poplars into agroforestry systems could be modelled taking advantage of relationship between the poplar genetic base and crown architecture plasticity (Ceulemans et al. 1990) and solid body canopy representations (Wilkinson 1995). This kind of model has been used to represent three-dimensional interception of light by poplar canopies (Chen et al. 1994, Castro & Fetcher 1998) and could be used to predict understorey productivity.

2.2.7.2 Poplar Agroforestry in New Zealand

New Zealand's poplar plantings have mainly been focused on shelter and control of hillside erosion using a variety of arrangements (Van Kraayenoord, 1993), while maintaining a predominant pastoral use (Mead 1995). In fact, poplars are scattered around farms supporting farming activity, and not as a farm operation on their own right, making it difficult to identify an isolated poplar agroforestry system (Garret & Buck 1997). Many poplars are used as small groups of trees to protect land sliding onto nearby constructions. Poplars are also planted on hillside paddocks, gullies, ponds, creeks and drains for stabilisation (Hicks 1995).

Although poplars have been used extensively used for many years in Europe, Asia and North America, there is very little published information about canopy shade and sheltering effects on the understorey in New Zealand. Poplar plantings on hillside pastureland appear to be a New Zealand first (Van Kraayenoord, 1993). Probably the observed effects on agricultural row planted or intercropped experiments cannot be directly extrapolated to the wide spaced plantings of New Zealand. In general, poplar-pasture interactions have not been particularly well explored and further research is required to support the sustainability of the past poplar conservation achievements from an economic and biophysical standpoint. The available information is presented in the following sections.

2.2.7.2.1 Pasture under poplars

Collateral pasture production under broad-leaved species has been found considerably higher than the figures reported for spaced and close planting of pine species (Miller et al. 1996). A five-year study under Italian hybrid black poplars at Muriwai, south of Gisborne, led to the derivation of a predictive model for East Coast pastures indicating that a planting density of 100 sph would reduce annual pasture production by 2% until canopy closure, or approximately 10 years after planting (NZPC 1995). At a planting density of 200 sph, the indicated pasture production loss was 24% by the time of canopy closure, around 8 years after planting (NZPC 1995). These losses can be partly offset, however, by the potential forage value of the tree prunings (Ayers et al. 1996), but this will depend on integration with other land-use enterprises (Mead 1995).

Gilchrist et al. (1993) compared pasture growth under individual poplars, willows and *Eucalyptus* growing on sunny hillsides and away from other trees. Apparently, *Eucalyptus* depressed pasture growth under their canopy more than poplars and willows. Nevertheless, this could not be attributed solely to the tree species, as each one was growing at a different site and only two trees per site were used. Pasture yield and legume proportion decreased within the proximity of the tree trunk suggesting that competition for moisture governed herbage mass. The distance from the stem did not significantly influence spring feed value of the herbage. The comparison of sunny and shady aspects of the tree did not show any difference. Overall, the data indicated that grasses and clovers could be suppressed by 12.5-21% in summer at 25-100 sph (Gilchrist et al. 1993).

Experience from England in the production of veneer peelers demonstrates the feasibility of poplar plantations as silvopastoral systems (Beaton 1987). After 8 years of initial small grain intercropping the area amongst trees was seeded with grass-clover and leased for grazing. With increasing shading during the growing season, together with a heavier leaf fall, the value of the grazing declined to a lower level about five or six years thereafter. At this point in the rotation the rental offered was approximately a third of the initial grazing value.

Woody and herbaceous perennials may interact when growing in the same space (Newman 1997). However, it is conceivable that some of these interactions might be overlooked, masked or only seasonally evident (Vandenbelt et al. 1990). Sometimes, an agroforestry mix could be located in a resource-rich environment where the various components each have sufficient light, nutrients and/or water (Ong 1994). Alternatively, the system under observation may be too complex to separate interactions and site effects of the individual components (Young 1997). For example, disentangling the relationships of fine root systems of trees and herbage appears challenging, but they are certainly important to understand water and nutrient competition (Ong et al. 1996). Pasture can provide strong competition against young trees, but intense competition from the tree can be expected once the tree and pasture roots meet and the tree canopy develops (Pollock et al. 1994). Soil's instability and erosion history, as in the case of soil conservation plantings can additionally complicate these relations.

2.2.7.2.2 Fodder from poplars

The agroforestry value of poplars is not limited to the understorey grazing. Wild animals and domestic livestock eat seedlings and saplings of *P. deltoides* (Holifield 1989). Trees grown for wood production are often pruned to produce a quality product and if palatable, can be eaten by stock, thus avoiding problems of reduced understorey production due to tree littering as in the case of pines with cattle (Reid & Wilson 1985). Tree litter from *P. deltoides* has been found to contain significantly higher N, P and K than *E. hybrid* at all stages of tree growth during 60 months (Singh et al. 1989). The litter of *P. deltoides* added (ha^{-1} yr^{-1}) 88.8 kg N, 43.6 kg P and 78.0 kg K as against 65.0 kg N, 23.8 kg P and 45.9 kg K by *E. hybrid.* The previous work exemplifies a model where deep-rooted trees can act as 'nutrient pumps' bringing nutrients to the surface via litterfall (Van Noordwijk & Purnomosidhi 1995). This model portrays trees as complementary, not competitive extractors of nutrients and water from the soil profile. However, there is evidence indicating that trees aggressively exploit the crop root zone and that the simplistic "pump" model should be used with caution (Vandenbelt et al. 1990).

Deciduous broad-leaved trees also provide pastoral farms with greater resilience to drought (Treeby 1978). Dry matter (DM) contributions from leaf material range from up to 2.5 t DM ha^{-1} at 594 sph in year 3 and increasing to nearly 9 t DM from 400 sph at year 11 (Kaul et al. 1983). Although poplar leaves are known to have tannins (Palo 1984), they form a reserve of nutritious (Reid & Wilson 1985, NZPC 1995, Ayers et al. 1996), reasonably digestible (Ayers et al. 1996) and palatable fodder available on the spot by lopping, or elsewhere by carting lopped food (Miller et al. 1996). Tree fodder during drought fits quite well within Government's policy position to encourage greater adoption of risk management practices, including self-protection, by producers (NZMAF 1997c).

A feed quality analysis on freshly senesced poplar leaves indicated a particularly rich content of minerals (McGregor 1989). Phipps (1989) also provided evidence of good feedstuff potential for poplar leaves from a drought rehabilitation programme, planting trees on fertile sheltered sites for fodder uses resulted in 52 kg of green leaves per low pruned Flevo poplar. Yield increases with tree age, and estimated yields of 1-5 kg DM can be expected from pruning every two years (NZPC 1995). Although, management of tree residue still represents a problem, the benefit of between 1000 to 3000 kg DM ha^{-1} yr^{-1} at a critical time when pasture supplies are short is unquestionable (McLeod 1985). Matsundana and Tangoio willows appear to provide easier grazing and fewer problems of branch disposal but had lower yield than Flevo poplar (Townsend & Radcliffe 1990). Other shrubs like Tagasaste yield 9000 kg DM ha^{-1} and have the advantage of remaining green and leafy (Wettenhall et al. 1997).

Silvopastoralism is not the only benefit that can be obtained from agroforestry and wide spaced poplars. Improved wildlife and animal husbandry environments are inherent benefits as well (NAC 1997c). Poplar canopies can provide shade, wind shelter and suitable wildlife environments (Garrett & Buck 1997). However, these benefits may have a sporadic occurrence since planted trees could be located in gullies that are already protected or exposed to gusty winds, where trees are of little help anyway (King & Sturrock 1984).

2.2.8 Alternative poplar roles towards sustainable agriculture

Bioremediation involves the use of biological diversity to reclaim habitats that have been contaminated by hazardous materials (Klopfenstein & Kerl 1995, Bull 1996). It shares with biorestoration the objective of stimulating the activities of indigenous organisms, or the introduction of extrinsic organisms, to effect *in situ* detoxification, mineralisation or bioremoval of pollutants (Bull 1996, Paul & Clark 1996). Traditionally, *P. deltoides* has been used for revegetating disturbed riparian sites and reclamation of strip-mined lands (Holifield 1989). *P. deltoides* has been planted successfully on mine spoils in Ohio both in pure or mixed stands and in mixture with *Robinia pseudoacacia* (Holifield 1989, Ditschl, et al. 1997). In a less conventional application, poplars have been widely used as phytoremediation tools because they are tolerant to high concentrations of organics (Schnoor et al. 1995).

A key attribute of the poplar in relation to bioremediation is the large quantity of contaminated water that it can take up from the soil (Newman et al. 1997). Hybrid poplar trees can uptake, hydrolyse, and dealkylate atrazine to less toxic metabolites (Burken & Schnook 1997). In addition, they can transfer oxygen to the root zone (Kozlowski 1997) for potential aerobic mineralisation of organics, and build-up of organic carbon in the rhizosphere due to root necromass, which retards the movement of hydrophobic organics and enhances the viability of beneficial microorganisms (Jordahl et al. 1997). Poplar trees have been found capable of taking up trichloroethylene (TCE) and degrading it to several known metabolic products: trichloroethanol, trichloroacetic acid, and dichloracetic acid. Poplars also have been shown to transpire TCE in measurable amounts (Newman et al. 1997). Poplar trees could enhance site remediation via contaminant uptake and in-plant degradation, by minimising off-site migration, or by enhancing microbial degradation in the rhizosphere (Jourdan et al. 1996). In a novel approach to bioremediation, molecular research is directed toward detoxifying environmental toxins such as TCE with genetically engineered *Populus spp.* (Stomp et al. 1994). In the future, agroforestry biotechnological research will provide more opportunities to incorporate new technologies from other areas of biological research (Bull 1996).

2.2.9 Amenity value

Economics and disease are not the only local factor against poplars (Reid & Wilson 1985, Wardrop 1993, NZMF 1996). Some European countries have prohibited the planting of poplars on floodplains to prevent the loss of natural vegetation and wildlife habitat and to maintain a natural appearance (FAO 1997). However, it is considered that poplars have added a distinctive profile to the New Zealand landscape (Barr 1996, Cowperthwaite 1994, Wilkinson 1996) and as such, they increase the landscape's complexity. Complexity is defined as the degree of variation derived from the visual qualities of intensity, contrast, and abundance within a scene (Orland et al. 1995b). Some studies suggest strong relationships between perceived beauty and complexity within a theoretical framework of human information processing (Orland et al. 1995a, Orland et al. 1995b, Orland 1997). Certainly poplars have an agronomic value, but historically, poplars have been shown to also have a high amenity value (Barr 1996, NAC 1997b).

2.2.10 Biochemical impact of poplars on soil traits

Trees have an impact on soil properties (Binkley 1995). Mature forested ecosystems are characterised by the accumulation of woody material and decomposed organic matter (Nair 1993, Kayahara et al. 1996), although fire history and climate vary accumulation. Acidification of the topsoil may result from coniferous (Hawke 1993, Yeates 1997) or mor-forming vegetation (such as northern indigenous forest of rata, kamahi, and rimu) in cold climates, and can trigger podzolisation (Rijkse 1977, Adams 1995). On the other hand there is the prevailing belief that hardwoods improve soils (Binkley 1995). However, fast growing trees and short rotations also have been related to the reduction of fertility (Madrigal 1995). This phenomenon is also observable in poplar plantations or in coppice broadleaf forests subject to short felling cycles (Bowersox & Ward 1977). In these situations nutrients removed during harvesting must either be generated naturally or restored by adding fertilisers or increasing rotation length (Hall 1997).

If given enough time, trees may play a role in the restoration of nutrients to sustainable levels after habitat alteration by grazing or other human activities have taken place (Nair 1987). The effects of grazing are not necessarily permanent but recovery may be on year to decade scales (Fleischner 1994). Reafforestation of degraded or agricultural land can improve soil structure, soil organic matter and nutrients, reduce runoff and increase soil water storage (Singh et al. 1989, Hall 1997, McIntosh 1997). It has been pointed out by Kaul et al. (1983) that the nitrogen recycling contribution to the soil from poplars could be as much as 43 kg in year 3 rising to 102 kg in year 11 of a *P. deltoides* rotations. Thevathasan & Gordon (1997) found similar nitrogen dynamics in poplar alleys. Work in a silvoarable poplar system showed that after four years of establishment, the soil within 1m from the tree rows had significantly higher soil organic matter and invertebrate populations (Park et al. 1994). In this work, the measures of soil organic matter and soil invertebrates were used to indicate the "health" of the detritus community.

Because grazed and forested ecosystems have different nutrient status, soil quality has been suggested as a sensitive and dynamic way to document the condition of the soils and how they respond to management change (Raison & Khanna 1995, Joshi et al. 1997). Biophysical characteristics can be used as indicators of present resource status and be related to sustainability (Lambert et al. 1996). The degree of soil disturbance during harvesting or livestock grazing, and the magnitude of change in soil porosity, organic matter content, nutrient-supplying capacity and ability to buffer acidification have been suggested as useful initial soil monitoring variables (McIntosh et al. 1997). However, development of the most suitable indicators requires good understanding of agro-ecosystem function (Amaranthus et al. 1994).

2.2.11 Conclusions

Poplar agroforestry can take different conformations, ranging from clusters to spaced plantings. Alternatively, they can be found forming lines of trees in shelterbelts, riparian banks, alley cropping or urban areas around houses. Poplar usefulness is not strictly tied to any system but can be a component of an integral agricultural system. Different benefits can be obtained, but most of the time the soil erosion control capabilities of poplars will be the most important in New Zealand conditions. Poplars are a multipurpose species in the sense that can be used for erosion control and livestock feed during sporadic drought emergencies while providing a land-stable grazing area. Management should be orientated to accomplish these roles and eventually provide wood material of adequate quality for sale.

Poplars have two major advantages over most temperate tree species, they can be easily established, and their canopy can be managed without compromising tree survival. Poplars can enhance the removal of xenobiotics by direct uptake and in-plant transformations to less toxic metabolites and by stimulation of microbial activity at no extra cost. Yet, they can also transpire large amounts of water increasing the bioremediation potential. These qualities propitiate the integration of poplars on farm waterways, undesired wet spots and erosion prone hill slopes.

The available evidence suggests that pasture under poplars may be constrained by shade cast by the canopy or leaf litter and moisture competition. The extent of reductions in pasture production under New Zealand conditions has not been completely assessed and research in this field is needed. Although poplars may have an impact on soil physiochemical properties, their significance in hill environments is unknown. Additional information will be useful to set guidelines for the management of poplar trees on farms.

Sustainable agriculture is a system of whole-farm resource use balanced with whole-farm productivity. The overall level of productivity achieved is dependent upon the ability to coordinate and manage simultaneously the soil, water, plant, and animal resources within climatic and economic limits. Both the kind and amount of plants and animals supported by the system are important and play significant roles, both individually and collectively in maintaining a healthy farm environment. Integrated systems could reduce human impact on resources while providing sufficient supplies of high quality food and fibre. From the information reviewed, it is concluded that poplars definitely have potential in sustainable agriculture contributing to economic and social wellbeing. However, information about the processes resulting in sustainability should be drawn in an integrative system approach in order to assess the potential of management options.

2.3 Tree mechanisms involved in soil conservation

Some erosion processes are more intense under pasture than under forest. Average levels of land slipping under pasture are between two and ten times greater than under indigenous forest or scrub for storm events of the same magnitude (Clough & Hicks 1992). Comparison between erosion that occurred under pine forest and pasture could be unfair. While new erosion is more probable under pasture, erosion under tree plantings usually is the result of re-activation of old debris avalanche scars on steep slopes (Hicks 1989b). Comparative studies in the Wairoa catchment, have examined erosion on forestry blocks established on less fertile, more stable and easier contoured tephra-covered sites, and pasture on the lower-fertility sandstone sites (Hendriksen 1995). Although the most fertile pastoral land was more susceptible to erosion, it was based on more erosion-prone siltstone and mudstone soils (Krausse and King 1997).

Tree root distribution and strength along with tree evapotranspiration (*ET*) are frequently cited as important qualities involved in soil conservation with woody species (Hathaway 1973, Ong et al. 1996, Grey 1996, Young 1997). Thus, the incorporation of trees may offer a sustainable approach for resource use on hillslopes (Hicks 1995). However, when livestock are introduced, the role of woody perennials in slope stabilisation, erosion control and watershed protection may be positive or negative (Shelton 1993). The tree mechanisms are revised here so as to attain a more complete understating of the complex role of trees in silvopastoral systems.

2.3.1 The role of tree rooting system

An increase in number and severity of landslides after removal of forest canopy is generally accepted (Trustrum et al. 1990, Marden et al. 1991, Smale et al. 1997). This has reinforced the common-sense expectation that tree root strength and transpiration are the major mechanisms intervening in the reduction of landslides (NZPC 1988, NZPC 1992, Huber and López 1993). These and other factors have led to the belief that trees growing on hillslopes inhibit shallow landslides in their vicinity (Hawley & Dymond 1988). However, tree root systems have been studied relatively little. Most of the work available in New Zealand is from *P. radiata* and in all cases, refers to the study of a few trees (Phillips & Watson 1994). Difficulties with excavation techniques and interpretation of tridimensional data have precluded full exploration of root morphology (Phillips & Watson 1994). New emerging technologies like computer modelling (De Reffye et al. 1995, Jourdan & Rey 1997a) and ground-penetrating radar (Fawkner 1997) are making it possible to assess spatial distribution and root biomass quantification. Root systems should have special consideration, given their importance on soil stability, water and mineral uptake and above ground plant growth.

2.3.1.1 Root morphology and growth

Three morphological types of tree root systems can be identified. *Taproot* is used to describe the main vertical root directly below the bole of the tree. *Sinker root* refers to other vertical roots coming either from the bole or from laterals. *Lateral root* refers to roots coming from the central bole but in the horizontal plane (Phillips & Watson 1994). The term *fibrous* usually is preferred to describe fine roots growing in the free fibrous rooting zone plane, which is the main site for nutrient and water absorption (Phillips & Watson 1994, Jourdan et al. 1995). Environmental conditions and genetic traits are responsible for the development of particular root morphologies (Sutton 1983). Root morphology dictates the long-term growth of the tree as well as its contribution to the slope stability plane (Phillips & Watson 1994).

Fibrous roots are important for soil conservation because they have been related to the soil binding capacity (Hataway 1973). In poplars, fine root biomass is difficult to assess and very dynamic due to its greater turnover rate in comparison with coarser roots (Lodhiyal et al. 1995). Studies have determined the quantitative genetic effects on adventitious rooting from poplar cuttings (Hataway 1973, Riemenschneider 1995). Heritabilities for root number and root weight have been linked to dominant (*P. deltoides*) and recessive alleles in other *Populus* clones (Riemenschneider 1995). Thus, some clones may be more suitable for conservation practices. However, no such work has been published from the newly released New Zealand clones.

Figure 2.4. Simulated 8 year-old oil palm plantation (143 sph) with root systems comprising primary roots only, seen from below. Root competition for space occurred in the topsoil, while downward growth is not impaired by tree competition (Jourdan & Rey 1997).

Root growth can be modified by competition for limited water and nutrients (Gregory 1996). Jourdan and Rey (1997ab) developed a computer model to identify different root types and absorption zones (Figure 2.4). Superficial roots are more active when nutrients and water availability is greater in the surface (Schroth 1995). The majority of the absorbing roots may occur within the soil under the tree crowns (Watson 1990). During drought or water stress, some trees can switch from the fibrous system to the taproot or a deeper rooting system (Allen & Grime 1995, Moreno et al. 1996, Green et al. 1997). Allelopathy either from roots and organs of plants or from decomposition also can limit root growth (Suresh & Vinaya Rai 1987). Poplars have allelopathic mechanisms (Shoup & Witcomb 1981) but probably they are not important for poplars in field conditions (Heilman & Stettler 1985).

The presence in the soil profile of stones, impermeable layers, high water tables (Phillips & Watson 1994) or compacted areas (NZMAF 1995) are probably the most common and widespread factors limiting root development. As with other tree species root development of poplar is limited by soil conditions (Hathaway 1973). Poplar roots tolerate extreme wetness, but do not grow within the watertable (Kozlowski 1997). Similarly, McColl (1973) found that *P. radiata* seedling dry root weights were lower with high soil water than with low moisture regimes.

The size of root systems is often reduced by competition of neighbouring trees (Eastham et al. 1988). In open-grown trees it is common to find lateral roots extending two or three times beyond the radius of the crown (Schroth 1995). Maximum lateral root extention was about 6 m and maximum vertical depth was about 2 m for poplars growing in a wet forest (Phillips & Watson 1994). However, Wilkinson (1989) argued that the poplars examined by Phillips & Watson (1994) were diseased and showed sub-optimum growth. Nevertheless, root extensions of 60 m have been recorded (Koslowski, 1971 cited be Hathaway 1973). Similarly, poplars can send their roots down more than seven metres for moisture if dry conditions predominate (Reid & Wilson 1985). Some poplars have an extensive root system that spread four times the height of the tree and the roots will sucker if damaged (Vanderpluym 1996).

Soil temperature is another factor that limits root development. Different studies have shown that *P. radiata* root growth is limited below 11°C, the optimum temperature being in the 11-14 °C range (Bowen 1970, Nambiar et al. 1979, Nambiar 1980, Nambiar et al.1982). Soil temperatures in New Zealand hill country usually go below 5°C during the winter season. Thus, a much lower root activity can be expected, and hence, lower transpiration during winter.

2.3.1.2 Root system and soil erosion

In forestry stands, the interlocking of adjacent tree-root networks reinforces the upper soil horizons and prevents the widespread evolution of a shallow landsliding plane (Phillips & Watson 1994). After canopy closure, further improvement in slope stability is not gained as the stand ages, although the influence of understorey vegetation is likely to increase (Watson 1990). However, it is proposed that if tree canopies are allowed to become too dense, groundcover will be reduced and erosion may be increased (Cameron et al. 1991).

Studies on *P. radiata* root development at Mangatu forest have shown that root biomass increases at rates of 1-2 t/ha/year from the time of planting to age 8-10 years, and then at 3-4 t/ha/year up to at least 25 years (Watson 1990, Phillips & Watson 1994). In subsequent rotations the period of risk is perhaps reduced as roots of harvested trees can provide residual but declining cohesiveness over the first 2-3 years of the subsequent rotation (Krausse, & King 1997).

Pearce et al. (1987) showed that although drier soil profiles and tree root networks affect only the upper 25-30% of an earth flow, their combined effects retard earth flow movement and sliding on basal surfaces several metres below the base of the rooting zone. Where a slip plane is present several metres below the surface, as in the tertiary mudstone country of the North Island, the number of deeply penetrating roots and their individual tensile strengths will possibly be the most important factors. Where the whole soil mass is very wet and earth flows are characteristic, the number of fibrous roots will possibly be the most important factor (Hathaway 1973). The importance of fine roots is reinforced by the work of Holifield (1989) showing that roots of established poplar seedlings were effective stabilisers of alluvial and dune soils.

Another study in a 7-year-old plantation of *P. radiata* at Haupapa, with 450 sph showed that the vertical distribution of the change in water storage was similar to the vertical distribution of root biomass for the upper 0-0.9m of soil (Whitehead et al. 1994). Ninety-eight percent of total fine root biomass, comprising 46% from tree roots and 52% from understorey species, was present in the 0-0.9 m strata. Below 0.9 m there were occasional tree roots but no roots from understorey species. This is consistent with a more detailed study of fine root distribution at Puruki, which showed that 92% of tree root biomass was in the upper 0.4 m and 53% in the top 0.1 m in a mature closed stand (Santantonio & Santantonio 1987).

Removal of forests results in a gradual reduction in root biomass and strength. Without root reinforcement, the soils on many slopes over 30° may suffer shallow landsliding during only moderate storms (O'Loughlin 1995). After logging, radiata pine root systems lose half their tensile strength within the first 15 months, and after 3 years the large (>5 cm diameter) structural roots are in an advanced state of decay (Phillips & Watson 1994). In general, roots of the faster-growing conifer (softwood) species tend to possess less tensile strength and therefore decay more quickly than similar-sized roots from the slower-growing hardwood species (Phillips & Watson 1994). However, for temperate climates, the rates of decay of root-wood appear to be similar, regardless of species or initial root-wood strength.

Miller et al. (1996) determined the relative efficacy of broad-leaved tree planting for earthflow stabilisation, in comparison with other stabilisation techniques such as contouring, graded banks and subsurface drainage, and afforestation with pines in a 12-year field experiment in the Waimata Valley. They concluded that contouring and drainage, while effecting temporary stabilisation, are in the longer term ineffective unless surface and subsurface waterways are regularly maintained. Secondly, close-planted broad-leaved trees are an effective stabilisation measure even in extreme conditions such as prevailed during Cyclone Bola. Thirdly, the effectiveness of the 6-10 year old, 5m spaced willows equalled that of evergreen trees studied.

2.3.1.3 Root system and tree survival

Tree survival and stability are as important as soil stability. Many of the sites needing erosion control in New Zealand are inherently wet and exposed to poor soil aeration. Oxygen availability is one element that determines root survival (Kozlowski 1997). Kramer (1951) demonstrated that flooding was followed by a rapid reduction in transpiration, a reduction in water absorbing capacity of roots and wilting of shoots. In some members of the species *Acer, Eucalyptus, Fraxinus, Populus* and *Quercus*, oxygen is supplied to roots by internal aeration by means of porous and adventitious roots (Janiesch 1991, Kozlowski & Pallardy 1997), although flood tolerance varies greatly with plant species and genotype. Leaf photosynthesis in *P. deltoides* was reduced by about 50% after 7 days of flooding, but recovered within 7 days after 28 days of flooding (Regehr et al. 1975). Very young poplar seedlings are more susceptible to flooding injury than older trees (Popescu and Necsulescu 1967). Soil inundation or high water tables also reduce root growth of most woody plants by inhibiting root formation and branching, growth of existing roots and *mycorrhizae*, and by inducing root decay (Kozlowski & Pallardy 1997). Similarly, improved pasture grasses (Davis & Martin 1947, Heinrichs 1970, Donohue et al. 1984) and legumes (Blaikie and Martin 1987) growing in New Zealand are relatively intolerant to poor soil aeration.

Poplar cuttings and poles have additional stability from the pole base and the development of a number of adventitious roots (Hataway 1973), while radiata seedlings have their dominant taproots removed in the nursery beds (McLaren 1993) remaining susceptible to topple and windthrow for about 4 years (Trewin 1995). It has been observed that poplars had less wind damage than conifers (Evans 1973). However, many trees may gain improved stability by increasing size and rigidity of stems and roots and the size of the soil-root plate (Blackwell et al. 1990). These anatomical modifications were observed in response to thinning (Wilson 1975, Fayle 1983). Some other trees like the shallow rooted Sitka spruce (*Picea sitchensis*) allocate more biomass to structural roots on their leeward side relative to the prevailing wind direction and may develop buttressed roots (Nicoll & Duncan 1996).

2.3.1.4 Root competition

Although it is generally accepted that roots of different plants may interact it is not well understood how tree roots and herbaceous understorey elements establish community interactions like competition, symbiosis or parasitism. The study of roots in agroforestry systems when crops and trees are grown concurrently is made more difficult because of the difficulties of distinguishing the fine roots of trees from those of crops (Gregory 1996). The case of root competition is perhaps the most studied to date. Root barriers have been used in an attempt to ascertain root competition between trees and a crop (Ong & Black, 1994, Ssekabembe et al. 1994, Ssekabembe et al. 1997).

Eastham & Rose (1990) in their classical work of tree pasture relations with *Eucalyptus grandis* and *Setaria sphacelala* cv. Kazungula, demonstrated that proximity to trees and increase in tree density reduced pasture root growth, with lowest concentrations of pasture roots occurring under the highest tree density. Although pruning trees may reduce above-ground competition between trees and crops, it may have negative effects, on root distribution and enhance below-ground competition (Van Noordwijk & Purnomosidhi 1995). In a short time frame, Hughes & Edwards (1994), showed the opposite effect when root pruning windbreaks in a kiwifruit orchard. The effectiveness of root pruning depends on the rooting characteristics of the trees and/or shrubs within the shelterbelt (Kort 1988). Ploughing between tree rows has been shown to be vital to reduce the growth of fine roots from poplar when intercropped, since this is a species capable of producing very dense root mats in the first 30 cm of soil (Newman 1997).

All these studies have shown that competition for water will be important when it is limiting. If the tree and the crop are able to exploit water at different soil strata, then a complimentary effect can be observed (Lott et al. 1996, Howard et al. 1997). Hydraulic lift, the transport of water from deep in the soil through plant root systems into the drier upper soil layers, has been demonstrated in several woody plant species (Dawson 1993), and constitutes another complementary mechanism by which herbage species can make use of underground water (Emerman & Dawson 1996). Very limited evidence is available as to how tree roots may interact with pasture species in New Zealand conditions (Gilchrist et al. 1993).

2.3.2 The role of evapotranspiration and the tree canopy

Trees of forested ecosystems represent a major route by which water in soils and groundwater aquifers re-enters the hydrologic cycle (Dawson 1996). Changes in vegetation influence the hydrological balance between precipitation, evaporation, interception, transpiration and runoff (Huber & López 1993). Trees can reduce drainage losses since they can utilise water outside the rooting zone of pasture species (Eastham et al. 1993). Improved rainfall utilisation can also occur via the substantial reductions in runoff, which can be achieved in agroforestry systems, particularly on sloping land (Young, 1989, Madrigal 1995). Generally, evapotranspiration losses are larger from forest cover than from other types of vegetation such as grass, pasture or scrub (O'Loughlin 1995). Grasslands established in New Zealand may suffer soil water imbalances, as reported in Australia, as a consequence of forest clearing. Transpiration is in many circumstances lower in trees forming a continuous canopy (Miller et al. 1996). Nevertheless, wide spaced trees have been used to increase water use in grassland ecosystems and lower water tables (Lefroy & Scott 1994, Walsh et al. 1995). The importance of the woody vegetation can be assessed using a representation of ecosystem water balance (Pilbeam et al. 1995).

2.3.2.1 The water balance model

The soil water balance, as a function of climate, irrigation and drainage, has a major influence on root functions (Van Noordwijk et al. 1996). Hence, a good characterisation of the water balance of a plant community represents a pre-emptive stage in the understanding of biological cycles and the development of agroforestry theories (Wallace 1996, Young 1997). As an example, the idea of the "safety-net" or that trees act as a 'nutrient/water pump' has been around for a long time (Vandenbelt et al. 1990). Nevertheless, little evidence is available that identifies the source of the water uptake of trees as from deep or superficial soil layers (Van Noordwijk 1989). Equation 1 shows the generalised mathematical representation of the water balance of an agroforestry system on a hillside (Wallace 1996).

$$T_t + T_u = P_g - I_t - I_u - E_t - E_u - D_t - D_u - R_t - R_u - \Delta\theta_t - \Delta\theta_u \qquad (1)$$

The gross precipitation P_g is first intercepted by the tree and understorey canopies, giving rise to interception losses from the trees, I_t, and understorey, I_u. The presence of the plant canopies modifies the rainfall so that the input to the ground beneath the trees, P_t ($P_t = P_g - I_t$), is different from that beneath the understorey, P_u ($P_u = P_g - I_u$). This input of water to the ground may infiltrate at different rates below the trees and crop, producing different rates of surface runoff, R_t and R_u respectively. In some circumstances F_t may be sufficiently high not only to reduce R_t to zero, but also to absorb any runoff (R_u) from the understorey area. Water will evaporate directly from the soil surface at rates E_t and E_u. The water contents of the soil zones beneath the trees, θ_t, and the crop, θ_u, due to the different surface inputs and transpiration rates, T_t and T_u, may lead to different drainage outputs, D_t and D_u. There may also be some lateral sub-surface water movement, R_s, particularly if the soil saturates for long periods (Wallace 1996). This model assumes independence between the θ_t and θ_u terms, a condition that cannot be met when the tree and understorey canopies are superimposed and also P_u will be equal to $P_t - I_u$.

Many of the philosophical and practical difficulties involved in partitioning light interception within agroforestry systems apply also to water, particularly when attempting to quantify the extent of the spatial and temporal variation (Ong et al. 1996). For example, when the main understorey species are herbaceous grasses and legumes, T_u, I_u and E_u are expressed in terms of understorey evapotranspiration (ET_u), as measurements of soil evaporation beneath a canopy of grass are not yet possible (Kelliher et al. 1993). Different approaches to the measurement of the water balance can be used depending on instrumentation and technical limitations (Ong et al. 1996).

2.3.2.1.1 Rainfall interception

Rainfall interception is the initial process by which trees have an impact on the water balance (Oyarzún et al. 1985, Huber & Oyarzún 1990). Rainfall interception has been extensively studied and considerable modelling has been done (Wallace 1996). An understanding of the processes controlling interception is of considerable interest to hydrologists because, in wet climates, this component can dominate total evaporation and explain why evaporative losses from forests can greatly exceed those from grassland (Calder 1990). Interception losses have been reported as 20% of the annual rainfall in Japan (Kondo et al. 1992) and up to 40% in the UK (Gash et al. 1980). A forested catchment has a 25%-30% lower water yield than a catchment in short pasture although the exact figure will depend on rainfall incidence, intensity and other factors (Maclaren 1995).

2.3.2.1.1.1 Modelling canopy interception

Recent modelling studies have incorporated a multilayer canopy and the evaporation rate in terms of the Penman-Monteith equation models to explain interception (Calder 1996, Watanabe & Mizutani 1996). Recent models consider the water storage capacity of the canopy, rates of evaporation, stem flow and water reaching the ground (Wallace 1996). The model used by Calder (1996) considered a Poisson probability statistic to describe the manner in which elemental areas of vegetation are wetted by raindrop strikes of different drop size. The model showed that canopy wetting will be achieved most rapidly and maximum canopy storage will be highest, leading to high interception losses overall, when both raindrop volume is small and the characteristic volume of drops draining from the canopy is also small. By contrast, when rain drop volumes and characteristic volumes are large, canopy wetting will be achieved slowly and interception losses reduced.

2.3.2.1.1.2 Measuring canopy interception

Interception can be estimated as the difference between P_g and throughfall. Apart from tree canopy interception, stem flow and forest litter also causes considerable interception (Huber & Oyarzún 1992, Kelliher, et al. 1992). Unfortunately, interception is usually combined together with runoff, infiltration or evapotranspiration when modelling hydrological processes relevant to hillside stability at the catchment level, and the significance of interception cannot independently be determined or predicted from watershed studies (Phillips & Watson 1994).

The importance of rainfall interception is demonstrated in a study assessing the effect of gorse canopies on throughfall and runoff in Northwestern Spain (Soto & Diaz-Fierros 1997). Annual average throughfall ranged from 54.7 to 59.9% and from 2.6 to 4.0 %for runoff in a 30% hill-slope, with an annual rainfall of 1063 to 1254 mm yr^{-1}. They concluded that throughfall is not linearly related to vegetation cover because an increase in cover does not involve a proportional reduction in throughfall. These authors found that an earlier development of Calder's model (Calder 1986) provided a good fit of the observed throughfall. This study explains why bush communities, like gorse, are useful for erosion control.

Tree branches and understorey debris can have an important effect on rainfall interception (Jackson et al. 1990, Kelliher, et al. 1992). Kelliher et al. (1992) studied rainfall interception by *P. radiata* and slash in a 450-sph plantation at Haupapa. From measuring the system's water balance throughout a year, they found that the measured fraction of rainfall intercepted by the stand canopy was 0.09. Stem flow was linearly related to rainfall, with maximum values (for rainfall of 91.4 mm) of 6.3 and 7.6 mm for trees that have been pruned to heights of 2-3 m and 3-5 m, respectively. Slash covered 60% of ground, with interception being 11% of rainfall in a stand basis. Although maximum canopy cover was only 24%, interception per unit of rainfall was similar to that of a closed-canopy *P. radiata* stand located near Canberra, Australia (Crockford & Richardson 1990). These differences could be accommodated into Calder's model (Calder 1996) given differences in the rainfall regime between these sites.

2.3.2.1.2 Water infiltration

When rainfall reaches the soil surface some of it may infiltrate into the soil. If the rainfall rate is greater than the infiltration rate the excess water starts to collect at the surface and when the surface storage is exceeded, runoff will occur. Infiltration is therefore a dynamic process that changes during the course of a rainstorm depending on the soil characteristics, slope of the land and the rainfall intensity (Wallace 1996). It is widely found, in both the tropical and temperate climates, that forested watersheds produce less runoff (Mclaren 1993, Phillips & Watson 1994). Canopy interception and direct transpiration cause the reduction in runoff, but the greater part of it results from higher soil infiltration capacity under trees (Walsh et al. 1995, Young 1997). Roots and stems increase the roughness of the ground surface and the permeability of the soil, leading to increased infiltration capacity and reduced soil erosion in ungrazed hill slopes (Phillips & Watson 1994, Alam, & Hosoyamada 1997, Young 1997). Furthermore, the forest topsoil is enriched with humus and has excellent structure, facilitating infiltration and absorption, so reducing erosion (Chen 1993). For a *Cacao-Erythrina* agroforestry in Costa Rica, observations were made of the hydrological cycle and leaching (Imbach et al. 1989). The canopy intercepted about 15% of the rainfall, 35% was lost by transpiration and 50% entered the groundwater. Belsky et al. (1993), also concluded that infiltration rate was improved under wide spaced savannah trees under low intensity grazing. Similar work at three stations in the Spanish Dehesa showed that for the soils in annual grasslands, the loss to drainage and surface runoff was considerable, equivalent to the total *ET* during 1984-1985, and 65-80% of that the following year (Joffre & Rambal 1993). Under the tree canopy, water loss to drainage and runoff was only 40 and 20% of *ET* during the same periods, respectively. Thus, tree cover considerably limited water stress on the vegetation of the Dehesa, and permits more efficient use of the limited water resource by the vegetation of this ecosystem (Joffre & Rambal 1993). However, Bezkorowajnyj et al. (1993) found that growth rate of tree seedlings and soil infiltration rate were reduced as a consequence of cattle foot traffic in Ontario, Canada; thus the animal interaction may counterbalance any improvement made by the trees.

2.3.2.1.3 Overstorey evapotranspiration

Once water is infiltrated into the soil it may be the object of competition among the different community species and then assimilated and evaporated through leaf stomata (transpiration) or may drain out of reach of plants. Transpiration rate is determined by the balance between atmospheric demand on the canopy and supply of water by the roots (Kelliher et al. 1993). The functional balance between roots and shoots allows plants to cope with soil water deficits (Kozlowski 1997). In planting large areas of trees, therefore, it is important to know the implications for evapotranspiration of adding or removing vegetation (NWSCO 1987). Basic knowledge on transpiration partitioning is required in order to integrate mixed plant communities into farming activities (Yunusa et al. 1997).

2.3.2.1.3.1 Meteorological estimates

Different methodologies may be adopted to determine transpiration of mixed communities. Transpiration may be estimated using transpiration models based on radiation interception by each component. For example, applying the Penman-Monteith prototype model (Ong et al. 1996) transpiration has been estimated at the leaf level (g_s) or at a canopy level (G_s). In a review by Kelliher (1993), analysed by Kelliher et al. (1995a) the maximum seasonal conductance of fully developed but not senescent leaves was defined as g_{smax} and G_{smax}. The parametres reflected variations between communities under optimum meteorological conditions arising from differences in plant physiology and leaf area index (Table 2.1). Vegetation types were aggregated into three superclasses: woody, natural herbaceous and agricultural crops. The G_{smax} values for the first two superclasses were statistically indistinguishable, but G_{smax} for agricultural crops were significantly higher. These analyses reinforce the importance of canopy interception when assessing differences in water balance and rainfall partitioning between forest and grassland ecosystems. Maximum hourly evaporation rates and surface conductances were similar for both ecosystems when soil water was not limiting (Kelliher et al. 1993).

Table 2.1. Superclasses and vegetation types with mean values of g_{smax} and G_{smax} for each type (Kelliher et al. 1995).

Superclass	Vegetation type and code	g_{smax} (mm s^{-1})	G_{smax} (mm s^{-1})
Natural herbaceous	Temperate grassland	8.0±8.0 (5)[a]	17.0±4.7 (5)
Woody	Conifer forest	5.7±2.4 (26)	21.2±7.1 (11)
Woody	Eucalypt forest	5.3±3.0 (6)	17.0 (1)
Woody	Temperate deciduous forest	4.6±1.7 (22)	20.7±6.5 (3)
Woody	Tropical rainforest	6.1±3.2 (17)	13.0 (1)
Agricultural crop	Cereals	11.0	32.5±10.9 (4)
Agricultural crop	Broadleaved herbaceous crop	12.2	30.8± 10.2 (5)

[a] Numbers in brackets are number of samples in each mean (species for g_{smax}, field studies for G_{smax}).

2.3.2.1.3.2 Sap flow estimates

Recently, the sap flow method has provided an accurate method for determining the vapour flux from the (dry or wet) canopy in a forest stand (Bréda et al. 1995, Arneth et al. 1996, Becker 1996, Granier et al. 1996b, Teskey & Sheriff 1996) or isolated trees (Caspari et al. 1993, Salama et al. 1994). It has been used for determining the transpiration of the overstorey in a multistorey stand (Köstner et al. 1992). The method allows the transpiration of a single layer in a given canopy or particular conducting root systems (Moreno et al. 1996, Green et al. 1997, Howard et al. 1997) or branches (Hinckley et al., 1994) to be measured separately. Daily total sap flow of the tree (Caspari et al. 1993, Čermák et al. 1992), or the stand (Becker 1996, Bréda et al. 1995, Čermák et al. 1995, Dunn & Connor 1993, Kelliher et al. 1992), in near ideal meteorological conditions has been reported for tropical and temperate vegetation.

2.3.2.1.3.3 Meteorological vs. Sap flow estimates

Estimating g_s or G_s is difficult to implement (Ong et al. 1996) and is only an approximation in mixed communities since the Penman-Monteith equation assumes a single hypostomatous leaf (Monteith et al. 1991). When comparing sap flow versus meteorological estimation of g_s and G_s, sap flow is more appropriate at the canopy or stand scales. Many canopies are so decoupled from the atmosphere that the main factors controlling water loss are net radiation and those factors that influence canopy boundary layer properties (wind speed and canopy roughness) rather than atmospheric saturation deficit (Hinckley et al. 1994). Use of G_s will be sensible only when changes in vapour pressure deficit and G_s largely explain variation in the stand transpiration during the day (Granier et al. 1996a). The dependence of transpiration on canopy conductance of climatic variables may be expressed as the "Omega factor" (Ω) (Jarvis 1976, Köstner et al. 1992). Values close to 0 indicate strong coupling between canopy and the atmosphere. In general, relatively smooth, uniform broadleaf canopies (e.g. tropical rainforest) have rather high Ω values, whereas rough, small-leaf canopies (e.g. orchard trees or conifer forest) tend to lower values (Hinckley et al. 1994). Studies by Hinckley et al. (1994) and Zhang et al. (1997) have shown that poplar canopies have a somewhat decoupled canopy (Table 2.2). Representative Ω values indicate variability for a given canopy in relation to hour of the day or canopy depth (Table 2.2). In addition, stomata from most pine species have been shown to be highly sensitive to soil water deficit. Hence, under Temperate and Mediterranean climates, adequate models of soil water regime are required to model forest canopy gas exchange on a seasonal basis because measurements based on the One Propeller Eddy Correlation (OPEC) system have shown strong limitations (Granier & Loustau 1994, Granier et al. 1996a). From the existing evidence, it appears that sensible estimates can only be obtained from water unstressed, coupled canopies by using the Penman-Monteith model or else use of sap flow techniques.

Table 2.2. Comparison of the stomatal de-coupling coefficient (Ω) in relation to sap flow and canopy conductance (g_c) with different woody vegetations. Source: Köstner et al. (1992), Hinckley et al. (1994), Arneth et al. (1996), Granier et al. (1996ab).

	n	Age	Height	Site	Leaf area index	Maximum sap flow rate (h^{-1})	Sap flow per day (stand)	Maximum g_c	Ω
Scots pine forest	24	33	12	Germany	2.9	0.33 mm	2-2.7 mm	0.9 cm s^{-1}	0.15
Tropical rainforest	8	---	---	F. Guyana	8.6	4 kg dm^{-2}	3.8 mm	0.8 cm s^{-1}	0.20
Poplar plantation	6	4	11-15	Ohio USA	---	0.085 kg dm^{-1}	3.6-4.8 mm [a]	0.48-0.074 mol m^{-2} s^{-1} [b]	0.66
Larix gmelinii	13	130	20	Yakust Russia	1.5	0.2 mm	2.3 mm	6.1 mm s^{-1}	
Beech forest	14	---	36	N Zealand	7	34.2 m	1.7-2.4 mm	12 mm s^{-1}	0.35-0.05 [c]

[a] For dominant and co-dominant trees.

[b] Declining values according to canopy depth , 1 mm s is approximately equal to 42 mmol m^{-2} s^{-1} at 20°C.

[c] Morning and evening values.

2.3.2.1.3.4 Transpiration and tree classes

From the different reports, there is a general agreement that differences in transpiration between trees are mainly accounted for by differences in tree shape and total leaf area of the trees, rather than the species (NWSCO 1983). Sap flow of individual sample trees reflects their social position within the canopy, where neighbours shade them or compete for soil resources (Köstner et al. 1992, Čermák et al. 1995). However, access to the transpiration at the stand level is an obvious difficulty arising when sampling complex forest ecosystems (Granier et al. 1996b). Similarly, it is known that water use decreases with stand age, explained by significant decline with age in the overstorey sapwood conducting area (Dunn & Connor 1993). In addition, the xylem sap flow activity has been generally regarded as negligible during the hours of darkness (Arneth et al. 1996), or has been ignored, although it may be nontrivial (Becker 1996) particularly when night-time wind speed is high (Malek 1992). Some authors have interpreted overnight sap flow activity, detected by the heat pulse or heat balance techniques, as recharge of the woody and leaf tissue that had become dehydrated during the day (Caspari et al. 1993).

Few measurements of transpiration have been made on individual mature poplar trees because of the limitations of the techniques and the size of the trees involved (Edwards & Booker 1984). At the stand level, Hinckley et al. (1994) estimated transpiration in the 3.6 to 6.8 mm d^{-1} range. Zhang et al. (1997) determined transpiration in a poplar agroforest in the range from 2.7 to 3.8 mm d^{-1}. In a poplar coppice regime, Hall et al. (1998) estimated that the mean daily transpiration was 6 ±0.5 mm d^{-1}. In New Zealand, there is the appreciation that mature poplars pump a lot of water out of the ground (Silverster 1994), but actual figures have not been reported. However, the appreciation might be right because Hall et al. (1998) indicated that the transpiration rates obtained with poplars were higher than any agricultural or tree crops grown in the UK. To the present time, no information regarding evaporative losses of poplars on hill slopes exists in New Zealand or elsewhere in the world.

2.3.2.1.4 Understorey evapotranspiration

When considering forest transpiration it is convenient to separate the forest into overstorey and understorey components of silvopastoral systems (Whitehead et al. 1994). Probably the overstorey uses substantially more water than the understorey for two reasons. First, the overstorey is exposed to higher irradiance, higher wind speed and lower humidity. Second, the overstorey is known to be deep rooted and consequently may suffer less water stress during summer as the soil profile dries out (Dunn & Connor 1993). However, the kind understorey can modify the overstorey transpiration as well (Miller et al. 1998).

Assessment of E_u can be made with micrometeorology or sap flow, although lysimetry and soil water or combinations of these methods are widely used (Eastham & Rose 1988, Whitehead et al. 1994). From partitioning studies it was demonstrated that pasture production under trees depends on competition between trees and pasture for water, light and nutrients (Eastham et al. 1988, Miller et al.1998). Trees reduce light levels on surrounding pasture, and may compete with pasture for water; both by canopy interception of rainfall, and by root uptake of soil water (Yunusa et al. 1995a). As tree density is likely to affect both the extent of tree canopy cover and tree rooting patterns, changing tree density, will modify the quantity of both water and light available to the pasture. Eastham et al. (1990) determined that tree-planting density modified productivity and water use of both trees and pasture, resulting in the understorey component becoming more important when tree density decreases. Tree transpiration, E_t and evaporation from the understorey, E_u, can be equally significant in the water balance of a forest where the trees are widely-spaced and tree leaf area index is low (Eastham et al. 1988, Kelliher et al. 1990, Kelliher et al. 1992).

The tree understorey may make a larger contribution to the water balance in sparse tree communities (Allen & Grime 1995). Kelliher et al. (1990) concluded that *P. radiata* understorey contributed considerably to the daily latent heat flux density. Interception and evaporation from tree debris may be as important as the canopies evaporative losses (Kelliher et al. 1990, Kelliher et al. 1992). Yunusa et al. (1995a) determined that soil water in a *P. radiata* agroforest was not affected by the pasture cover treatments when rainfall was frequent and *ET* exceeded the evaporative demand. However, the pastures dominated the *ET* when rainfall was less frequent (Miller et al. 1998). Pasture evaporation constituted at least 50% of the total water use from both ryegrass/clovers and lucerne ground covers in summer and autumn (Yunusa et al. 1995a). Comparison between open pasture and oak understorey has found that the soil water content was often higher in the understorey soils (Jackson et al. 1990, Joffre & Rambal 1993). However, moisture retention was greater, as indicated by soil matric potential values closely paralleling those in the open grassland (Jackson et al. 1990). Another dynamic aspect of the silvopastoral understorey is the grazing activity of livestock. Livestock grazing may reduce herbaceous plant water use by removal of leaf area and by subsequent reduction in plant root growth (Karl & Doescher 1993).

2.3.2.2 The role of canopy shading on understorey

Tree canopies in forested ecosystems may modify the microclimate in such a way as to increase the overall water use efficiency (McIntyre et al. 1996, Young 1997). Reduced soil evaporation increases water available in the soil for transpiration by the understorey or the trees (Radcliffe 1984, Eastham et al. 1990). Shading of the understorey may reduce surface soil and air temperatures to give beneficial, or detrimental, effects on understorey growth (Belisky 1992, Wallace 1996). Another form of microclimatic modification which may improve transpiration efficiency is the reduction in the within-canopy vapour pressure deficit resulting from transpiration from the second canopy and/or soil evaporation mainly by reductions in wind speed (Sturrock 1969, Grace 1988, Smith et al. 1997). Monteith (1988) showed that transpiration efficiency is inversely proportional to the vapour pressure deficit of the air, that is, plants use more water to fix a given amount of carbon when the air is drier. Reponse of crops to shelter or shade from trees is therefore quite variable. Rosenburg et al. (1983) suggested that shelter might in many cases not cause a significant reduction in evapotranspiration over the season for a field crop. Walsh et al. (1996) suggested that tree transpiration and surface shading may reduce salt accumulation at the soil surface and promoted the re-establishment of pasture communities in a form of agroforestry in Australia.

Shading affects understorey crops by reducing temperature and the amount (and quality) of light (Vandenbeldt et al. 1990). Shading of the understorey may also reduce its transpiration without a proportional decrease in photosynthesis (Wallace 1996). This would occur if the understorey species became 'light saturated' at relatively low radiation levels which is typical in C_3 species (Squire 1990). Deciduous trees have considerable potential for integration into agroforestry as they tend to use growth resources for only part of the year, thus allowing resource use by adjacent or understorey pasture or crops to take place with minimal interference (Newman 1997).

2.3.2.2.1 Plant physiological mechanisms under shade

Discerning the operating physiological mechanisms in plants shaded by trees is complex. Some competition for nutrients will occur in experimental studies if the root systems are not physically delimited (Ssekabembe et al. 1994, 1997). Even then, complications arise when assessing the amount and quality of radiation available to the understorey. In addition, no genetic variation in morphology and physiology in response to environmental variation; a phenomenon known as phenotypic plasticity has to be accounted for (Abrams 1994).

Almost all understorey plants endure shade, interrupted more or less frequently by sunflecks. Sunflecks are defined as "fast excursions of high light above a dim light background" (Pearcy et al. 1994). The term lightfleck is used to refer to artificial light or a high intensity light pulse originating from indirect light. The duration of sun-flecks and lightflecks has the order of seconds, rarely minutes (Pfitsch & Pearcy 1989). In temperate and tropical forests, sunflecks contribute between 30 and 80% to total daily photon flux, and probably a large fraction of carbon gain is attributable to sunflecks (Chazdon 1988). Daily and seasonal variations in sunflecks occur. For deciduous trees even during winter in an open wood, the trunks and bare branches will cut off an appreciable amount of light (Anderson 1964).

Utilisation efficiency of lightflecks by leaves increases with decreasing duration of the lightfleck, and depends on the photosynthetic induction environment (Küppers et al. 1996). Leaves predominantly exposed to sun and shade differ with respect to photosynthetic induction (Pearcy et al. 1994). Shade leaves may become fully induced by a series of light pulses, whereas photosynthetic induction of leaves from partial shade or full sun depends on continuous light. Ellenberg (1963) using *Asperula odorata* in mixed beech forest found a very rapid increase in transpiration of plants in the forest when struck by a sunfleck. Additionally, shade leaves maintained a higher induction state over longer periods in dim light or darkness than sun leaves (Ellenberg 1963). Both features are advantageous to shade leaves in a highly dynamic light environment (Küppers et al. 1996). Shade-tolerant plants may have higher quantum efficiency and lower respiration rates under low light conditions (Teskey & Shrestha 1985). Legumes like lotus and tagasaste have shown good persistence in *P. radiata* agroforests (Gadgil et al. 1986). However, leaves of grasses (like ryegrass) that emerge in partial shade have a lower photosynthetic potential than leaves that emerge in full sunlight (Woledge, 1972 Parsons and Robson, 1981). Shaded ryegrass tillers can survive for up to five weeks, but severely stressed tillers eventually die (Ong & Marshall, 1979). In a sunfleck, the proportion of red to far red light is not widely different from that in the open, and short term intense dosages of particular wavelengths appear to be sufficient to reset morphogenetic processes (Anderson 1964). This may explain in part why ryegrass can be found as part of an understorey shaded by trees (Kellas et al. 1995).

The distortion of the seasonal pattern of light under a deciduous canopy affects not only the periods at which most energy is available for photosynthesis, but also the long wave energy balance, diffusion of water vapour, carbon dioxide and the daily and seasonal variation in temperature (Anderson 1964). In spite of these considerations a practical investigation of sunflecks remains out of reach in many situations. A more practical and popular approach is the use of shade cloth as an approximation of shade conditions prevailing in forested environments (Kephart & Buxton 1989, Wilson & Wild 1994). With a physical filtering layer on top of the understorey canopy, it will be only possible to investigate predetermined shade intensity and wavelength pattern.

2.3.2.2.2 Canopy shading and silvopastoral systems

Traditionally, grasses and herbaceous legumes have been the major components of pasture, but sustainability constraints have increased awareness about a more direct role of trees in agricultural and pasture production systems (Atta-Krah 1993). *P. radiata* studies have demonstrated that herbage yield decreases as crown density increases (Anderson and Batini, 1983 1984, Pollock et al. 1994, Braziotis & Papanastasis 1995, Hawke & Knoweles 1997). The same trend was found with increasing pine age although there might be a small increase in the yield compared to open areas in the first years (Hawke, 1989). Whether or not the tree canopy provides a suitable environment for pasture development largely depends on tree planting density and stand age (Mclaren 1993). Results from an agroforestry experiment at Lincoln, New Zealand showed that forage production from a newly established pine-pasture system did not differ greatly between pasture types during the first 3 years (Pollock et al. 1994). At the same site, Yunusa et al. (1995b) concluded that the growth of understorey species was less susceptible to the adverse effects of competition for soil water with *P. radiata* than they were to shading by the tree crowns. These results were similar to those obtained by Anderson & Batini (1979). A long-term experiment at Tikitere, New Zealand examined the effects of *P. radiata* on pasture production showing increased loss in pasture production associated with increased density, age and slash (Percival et al. 1984, Knowles et al. 1995, Hawkes & Knowles 1997). Results from *P. radiata* agroforestry experiments in Australia also found pasture reductions but a later tree age (Anderson & Batini 1983, Anderson & Moore 1987, Kellas et al. 1995). Because the Tikitere experiment was a highly productive site (mean annual rainfall 1500 mm), the impact of *P. radiata* trees on pasture production occurred early during the rotation (Kellas et al. 1995). With deciduous tree species, pasture production is also reduced (Ditschl et al. 1997), but forage production can be regained by thinning or pruning or using short rotations or coppicing (New 1985). *P. radiata* research and broadleaf research of Gilchrist et al. (1993) could not discern what was the important source of competition: light, moisture or nutrients.

2.3.2.2.3 Canopy shading and pasture nitrogen

Shade has also been found to increase the N content of pasture grasses (Wilson et al. 1986, Cameron et al. 1989). It has been observed that for some grasses, herbage growth was greater for sun tolerant pasture grasses under shade than in full sun, in N-limited situations (Wilson & Wild 1991). Current evidence suggests that better performance under shade is more likely to be driven by differences in mineralisation rates and not enhanced photosynthesis (Wilson & Wild 1994). However, van Soest (1994) points out that cloud cover or shade, will tend to decrease the nutritive value of forage. Nitrate accumulation in forage is greatest under cool, cloudy conditions, which decrease photosynthesis and convert amino acids to nitrate.

Similarly, higher N availability in soils under artificial- and tree-shaded environments has been reported for a number of situations, e.g. in Australia (Wilson et al. 1986, Wilson & Wild 1991), East Africa (Belsky et al. 1993), the Mediterranean (Joffre et al. 1988) and the Caribbean (Cruz et al. 1993). These reports were generally associated with water-restricted environments, while the gain in fertility is often ascribed to tree factors such as tree litter fall, bird droppings and camping animals. Although several explanations have been offered for this phenomenon of microsite enrichment, the interactions involved are highly complex (Ong et al. 1996).

2.3.2.3 Influence of canopy shelter on plants

Tree canopies can provide a sheltered environment while they reduce wind speed and buffer air and soil temperature fluctuations (Grace 1988). Shelter effects and characteristics are better understood within the windbreak configuration (Byington, 1990). Windbreaks increase yields of field and forage crops by reducing wind erosion (Cook & Grut 1991, Farmer 1992), improved microclimate (Easterling et al. 1997), snow retention and reduced crop damage by high winds (King & Sturrock 1984, Kort 1988). Most beneficial effect is gained from less stressful evapotranspiration conditions (Sturrock 1969). However, protected actively growing crops may in fact have a higher water requirement (Ong et al. 1996) because crop stomata remain open and decoupled from the atmosphere (McAneney et al. 1992) or because the 'protective' trees increased their transpiration (Smith et al. 1997). Such plants utilise more carbon dioxide and more water than exposed plants, thus increasing in size and furthering the demand for water (Sturrock 1969).

The type of trees and shrubs planted also affects windbreak efficiency (Gregory 1995). Efficient conformations generally have a permeable structure (Quam et al. 1997a). Often, best results are obtained when both conifers and broad-leaf species grow together in windbreaks (Byington, 1990). The siting length, height, and density of a windbreak determine the protected area (Gregory 1995). Windbreaks protect cropland by reducing wind velocities for a distance approximately 15 times the height of the tallest trees (H15) while 20H still offers suitable shelter for animals (Gregory 1995, Quam et al. 1997b). Wind protection depends on the number of tree rows (Vanderpluym 1996), but production is compromised by the space that the windbreak uses as well (Kort 1988). Although shelter mechanisms on flat land are widely studied, this is not the case with the steeper and more broken country. While on the plains some 3% of the land area of a farm in trees may suffice for shelter, in the hills the figure may need to be 20% or more (King & Sturrock 1984).

2.3.2.4 Influence of canopy shelter on animals

Windbreaks are usually planted and managed as part of a crop and/or livestock operation to enhance production and protect livestock (Quam et al. 1997b). Recently, animal welfare has become an overseas marketing issue for New Zealand animal produce (NZMAF 1996a). Many farm operations lack enough shelter and shade for livestock compromising animal welfare of young or susceptible individuals (NZMAF 1997f). In New Zealand, estimates of up to 30% losses of lambs as a result of exposure or starvation (Dalton et al., 1980) are commonly reported. Reducing wind speed increases feeding efficiency (Elvidge & Coop, 1974) and lowers animal stress and mortality (Holifield 1989, Quam et al. 1997b).

Figure 2.5. Sheep crowds around a cluster of *P. nigra*. In the background, some visible signs of old soil slips. Manawatu, New Zealand 1996.

Adequate shade is important in hot sunny weather, sheep in full wool and any stock suffering from facial eczema (NZMAF 1996). Sunburn is the most consistent sign in facial eczema (Brightling 1988). Photosensitization is particularly distressing and debilitating in deer (Mortimer 1987). Treatment for these illnesses include retiring the animals from the infected paddock, offer shade and drenching with zinc oxide (Brightling 1988). Nevertheless, some shelterbelts have been associated with facial eczema outbreaks.

While windbreaks are primarily planted to protect farmsteads, livestock, roads, or crops, they offer wildlife benefits without compromising the main purpose (Quam et al. 1997a). Many species may use windbreaks as travel lanes between feeding sites, as protected cover at feeding sites, and as routes for safe dispersal. Planting a variety of deciduous tree and shrub species will provide a habitat structure with a large selection of vertical and horizontal nesting and foraging sites (Johnson et al. 1997).

2.3.3 Conclusions

The detailed mechanisms of how tree roots contribute to hill slope stability are not particularly well understood, although it remains unquestionable, the value of well stabilised trees in controlling soil erosion. Current knowledge indicates that environmental factors largely control the final pattern of root morphology and root density. Under some conditions, root systems can control erosion events, given good tree establishment and anchorage. The scarcity of published information does not provide statistical evidence to support any particular species as superior for land stabilising purposes, although poplars have morphological and physiological advantages. Planting methods and anatomical fitness may affect tree survival. Tree roots may interfere with pasture growth, through nutrient and water competition. Although poplars may enhance soil fertility via litter decay, trees probably will compete with the pasture understorey for nutrients in a depleted slip scar environment.

Tree canopy characteristics and activity determine to a great extent the water balance of a given ecosystem. Different forest communities will have a different impact on the partitioning of the rainfall and outcome of a catchment water yield. At the present time, no information regarding the water balance of tree/pasture hill slopes exists in New Zealand. Trees, when acting as an active overstorey may capture important quantities of light. However, the understorey may have a major contribution to the partitioning of plant transpiration. Light in form of sunflecks should not be underestimated, as it remains an important source of light for understorey communities. Shade through transpirational and sheltering mechanisms may prove an advantage to human, animal and plant populations. However, gained benefits are accompanied by some degree of competition for resources. Available knowledge on canopy transpiration and root water uptake, regulation and competition processes comes from sites on flatland and rather homogeneous ecosystems, making it difficult to assume similar relations on hill slope scattered tree communities.

From the information reviewed, it is concluded that the integration of poplar trees into farmland activities has the potential to contribute to soil biophysical sustainability. The concomitant tree interactions with the other productive components of the system (pasture and animals) need to be explored and quantified. The mechanisms of interaction need to be identified so as to provide adequate management options to minimise negative effects. Poplar contributions to the ecosystem need to be better understood in order to fully evaluate its integration into the pastoral land use and the consequences on biophysical, economic and social aspects of sustainable resource management.

2.4 Erosion in the Hill Country

The total land area of New Zealand is approximately 27.1x10^6 ha. Over 13.6x10^6 ha (51%) is used as pastoral and arable land, with around a further 28% covered in forest (NZMAF 1997d). Most of the country is mountainous and hilly with over two-thirds at a slope greater than 12° and nearly one-half at a slope greater than 28° (SNZ 1993). Defining hill country as all the land with slopes between 12 and 28°, some 3.5x10^6 ha in the North Island and 2x10^6 ha in the South Island fall in this category, land with steeper slopes is normally termed hard hill country or mountainous terrain (Molloy et al. 1980). The hill country could be considered the backbone of the meat and wool industry and as such, has a particular relevance for economic development (NZMAF 1996b).

Like most of New Zealand, the hill country environment has undergone long-term geomorphological changes governed by tectonics, rock type, vegetation, and climate and, in the last 150 years, pastoral farming enterprises (Mackay et al. 1995). The traditional European settlers attitude towards the forest was of an impediment to progress (Pearse 1995). It was calculated that 7x10^6 ha (about half the forested area present in 1840) were cleared following European settlement (Newsome, 1987). High yielding pasture has been maintained with large fertiliser inputs and grazing management (Edmeades & Brown 1986, O'Connor et al. 1996). Lime and fertiliser applications are necessary to maintain the chemical fertility required for pasture production (Edmeades 1986). However, after economic reforms (NZMAF 1997b), many farmers reduced fertiliser maintenance inputs when income was low, in an attempt to preserve farm income (NZMAF 1996b) and increased off farm activity (NZMAF 1997e). In the absence of effective grazing management and/or fertiliser, all hill country areas that were previously in forest have a tendency toward reversion to woody shrubland trees (Eyles & Newsome 1992, Smale et al. 1997).

2.4.1 The erosion process

As hill country grassland developed, the soil resource has been lost at one of the worst rates possible (Hendriksen 1995). All of the most important hill country regions are highly susceptible to soil erosion, as most of them were forested land (Purey-Cust & Hammond 1995). Nevertheless, many farms have remained productive over the time (OECD 1997ab). This has been possible by implementing land conservation practices or allowing parts of farmland to revert (Hicks 1989b), or judiciously using fertiliser inputs (Mackay et al. 1995). A survey in the 1970s indicated that erosion was extremely severe only on 13% of the susceptible land (Hicks 1995). Another survey showed that an important area of pastoral land is limited, or incapable, in sustaining pastoral use (Eyles & Newsome 1992). It was considered that almost 28% of farmland needs substantial soil conservation measures. Eyles (1993) identified the highest level of sustainable use that parcels of land can achieve. A total of $9.1x10^6$ ha required no major modifications to current land use. However, there were $4.5x10^6$ ha from the total used as pastoral and arable land that needed modifications to match its sustainable land use rank. In some areas, pasture production has declined by up to 30% on moderate slopes and up to 60% on steep slopes as direct consequence of erosion (Mead 1995). Soil erosion resulting from human activity can be as much as 100 times the natural erosion rate (NHDES 1997).

2.4.2 Grazing and soil erosion

When forested hill country was converted to pastureland the physical constraints of slope stability, soil fertility or vegetative covers were not considered (Eyles & Newsome 1992). Trustrum et al. (1990) and DeRose et al. (1993) have shown that on hill slopes >42° soil losses exceed soil formation. On slopes of 28-42° it was suggested that soil loss limits pasture growth and still contributes to sediment loading. Nevertheless, on slopes <28° land is capable of sustaining pasture production on the grounds of potential soil regeneration rates. Steep slope depressions where subsurface water accumulates are the specific slope localities most susceptible to failure. Deep-seated slumps and earthflows on weak rocks in the eastern North Island may activate after forest removal on relatively gentle slopes of less than 25° (O'Loughlin 1995).

Although pasture reduces erosion hazard in its own right, efficiency is strongly dependent on slope and system and intensity of grazing (Garrity 1996). Lambert et al. (1985) measured soil losses of 2.7 t ha from hill land (21°) under intensive cattle management. Associated with this loss of topsoil was an annual loss of 12 kg N and 1.5 kg P ha^{-1}. The amount of soil slip has been shown to increase until a slope angle of 30° above which there is no increase in density of soil slip (Hendriksen 1995), mainly because previous storms had already removed much of the regolith (DeRose et al. 1993). At low slope angles and under ungrazed improved pasture, levels were very low (0.07 t ha /event) (McFadgen 1989). This increased with grazing (1.41 t ha event) and where pasture was depleted or overgrazed (4.12 t ha event), and was greatest on steep slopes (4.42 t ha event at 33°). Unfortunately, close grazing during winter is the rule rather the exception in the pastoral system in New Zealand. Animals are restricted in herbage intake during this time and post-grazing residual masses are usually in the range of 900-1800 kg DM ha, for sheep and cattle operations (Poppi et al. 1987).

Improper grazing management damages the soil structure by pugging and slipping (NZMAF 1995). Edmond (1958) concluded that pasture regrowth during winter and spring was decreased by almost 50% when sheep treading increased from a stocking rate of 0 to 20 su (sheep units)/ha.

2.4.3 Influence of soil erosion on pasture productivity

Slipping has a significant impact on pasture productivity in the short-term and potential productivity in the long-term (Singleton et al. 1989). The study by Douglas et al. (1986) of pasture production in the Wairoa District indicated a minimum of 15 years to recover pasture productivity to a steady state after slipping. Photographic records have shown that slip healing may take much longer (Fransen & Brownlie 1995). Landslide scars may recover 70-80% of the production potential of remnant forest soils over the first 20-40 years but there is no further recovery up to 100 years thereafter (Trustrum et al., 1990). Maximum recovered productivity under normal management is likely to be at least 20% below original (Douglas et al. 1986). Unattended erosion may increase as a study in the Waihora catchment revealed an increment of 72% in erosion severity over a 10-year period (ECCB & RWB 1988, Figure 2.2).

2.4.4 Soil erosion causality

The causes of erosion and the reasons for hill country susceptibility to erosion are complex (Grant 1989). They include the underlying geological structure, climate, vegetation management and other land-use practices (Rijkse 1977, Harmsworth et al. 1987, Krausse & King 1997). Erosion is by nature episodic and the risk of occurrence can be quantified in terms of frequency and of magnitude (Krausse & King 1997).

Evans and Fukuoka (1995) studied the relationship between volume (magnitude) and cumulative number of the major landslides larger than 20×10^6 m^3, which took place between 1900 and 1992 in the world. They showed a clear power-law relation, meaning that the magnitude of landslides had a fractal structure regardless of geology, meteorology environment, and triggering mechanism. Similar analysis of published statistics of landslides in Japan, New Zealand, and Swiss Alps showed that all of them have power-law relation and they have almost the same fractal dimension (Omura 1995). In New Zealand, fractal dimensions reflected a strip pattern of landslides located on the border of tectonic layers.

Previous study of alluvial soils in New Zealand by Grant (1989) determined that climatic variation accounts for an alternation between short periods of net erosion, and longer intervals of net soil formation. Studies of historical deposition showed that over the centuries, erosion has occurred independently of land settlement and was catastrophic rather than insidious in nature (McFadgen 1989). Erosion is not limited to pastoral land, channelised mass movement (debris avalanches and flows) have occurred in the Raukumara and Ruahine range areas under intense rainfall events, and may contribute 1500-4500 m^3 km^2 yr^{-1} of sediment to watercourses (James 1973, O'Loughlin et al 1984, Grant 1982). Erosion from indigenous forest has been attributed to introduced mammal activity (James 1973). Indigenous forest erosion may result in compounded erosion of the pastoral hill slopes and inundation of the intensely cropped downstream flats by floodwaters and silt (Hendricksen 1995). Eventually, land-use, vegetative cover and soil conservation techniques do not change the frequency of erosion but strongly effect its magnitude (Clough & Hicks 1992). Poor planning and marginal land use practices will tend to exacerbate the effect of catastrophic phenomena, as Cyclone Bola has demonstrated.

2.4.5 Soil erosion off site repercussion

Widespread soil erosion results in an adverse visual impact (Orland et al. 1995a), reduced productivity and number of negative externalities (OECD 1995). Disruption of aquatic ecosystems through increased flow variability and flooding, or increased nutrient loading of waterways are some of the offsite effects of erosion (NZMAF 1992). Suspended solids affect the colour and clarity of water and are considered an indicator of the nutrient loading. Water from the Manawatu River during low flow periods appears clear, yet suspended solids are present in concentrations of <2 g m^3 (MWRC 1994). A flood of a size that could be expected about once a year at Palmerston North, will have suspended solids concentrations of about 5,500 g m^3 (MWRC 1994). Much of the sediment generated by this erosion ends up in watercourses and on floodplains. Page et al. (1994) examined sedimentation rates in Lake Tutira, a closed catchment, where approximately 57% of eroded material made its way into watercourses as a consequence of Cyclone Bola. Page & Trustrum (1997) used late Holocene lake sediments to determine the erosion response of the steepland catchment to land use. Sedimentation rates under pastoral land use (A.C. 1878-1985) were between 5-6 times the rate when the land was under fern/scrub (c. 560 yr B.C.-A.C. 1878) and 8-17 times the rate when under indigenous forest (1850-c. 560 yr B.C.).

Unfortunately, soil erosion awareness only increases in the wake of catastrophic phenomena after media releases (NZME 1996). Most of the published erosion reports refer to inflicted damage after severe storms (Hicks 1989abc, Phillips et al. 1990, Watson 1990, Marden et al. 1995 Krausse, & King1997). Much of the recent information available about erosion damage on hill country grassland came from the experience of Cyclone Bola in 1988 (Hicks 1989abc Marden et al. 1995). It could be argued that storms of the dimension of Bola are rare. However, erosion of equal severity occurs during lesser magnitude, more frequent winter (Hicks 1989c) or summer (Page et al. 1993) storms over smaller areas.

Kelliher et al. (1995b) developed a model predicting the probability of the occurrence of extreme flood using historical discharge rates of the Waipaoa River as a continuous function of time (Figure 2.6). The model suggests that there is a 25% probability of an extreme flood every year and it will be expected almost with certainty every decade. The model implies that any inflicted damage should recover over 10 years at the most.

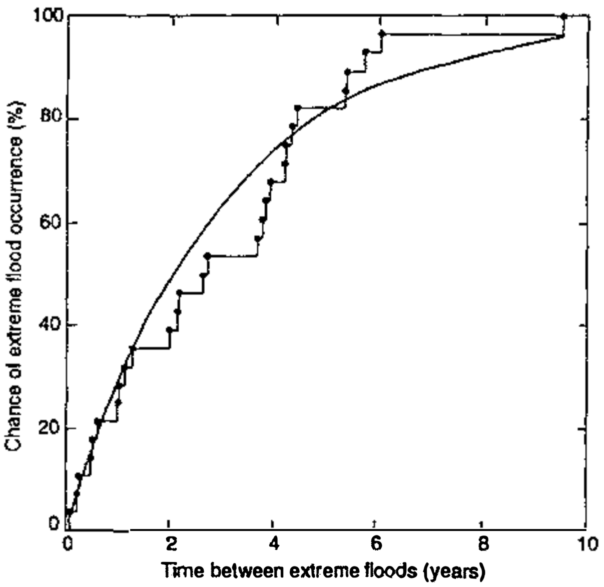


Figure 2.6. The relationship of time between extreme floods of the Waipaoa River at Kanakanaia (discharge rate >1500 $m^3 s^{-1}$) and the chance of their occurrence. Analysis is based on time intervals between twenty-nine 20th century extreme floods. The lighter step function is the observations (data shown as symbols) and the heavier curve gives expected chances for the cumulative exponential probability of the proposed model (Kelliher et al. 1995).

2.4.6 Conclusions

Hill pastures constitute a substantial proportion of New Zealand pastoral land use where soil erosion has been one of the costs of agricultural development of hill country. Along with recurrent extreme climatic phenomena, the pastoral practice has reduced the ecosystem resilience. Adoption of sustainable practices and restorative approaches will limit the encroachment of erosive processes on susceptible hill slopes.

The hill country experiences a variety of soil erosion processes with sporadic but certain occurrence. The pastoral land along with natural weather and geological foundation triggers erosion events. Careful planning in land use should be considered in the light of the erosion damage inflicted in the past and the current land use trends.

It is clear that negative externalities not only deteriorate the farm economic status. In the international arena the "green clean" and "environmental friendly" images may lose credibility as well. Erosion environmental impact has strong repercussions at infrastructural, demographic and economic levels, and deserves careful examination. Assurance of sustainable land use can only be achieved by means of practical ways to preserve the land. Sustainability at the farm level is a requisite, since the farm holding is the minimum land unit where the principles of sustainability can be applied.

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3. Rainfall partition in a poplar-pasture system

3.1 Summary

Traditionally poplars have been planted to control erosion in New Zealand hillslopes because of their capacity to dry out and bind together the soil by reducing effective rainfall, increasing evapotranspiration and soil strength. Surprisingly the effect of wide spaced poplars on the soil water and rainfall partitioning has not been reported. This study determined the rainfall partitioning for 18 mid-spring days in an I78 clone *Populus deltoides* (Bart.ex Marsh)-pasture association (37 stems per hectare, unevenly spaced at 16.4 m ± 0.4 apart) and compared it with a traditional open pasture system in grazed areas of a hill environment.

Evapotranspiration was greater for the poplar-pasture association (2.7-3.0 mm d^{-1}) than for the open pasture (2.2 mm d^{-1}). The tree canopy alone contributed 0.92 mm d^{-1} as transpiration and 1.37 mm d^{-1} as interception, whereas the pasture understorey evapotranspiration was only 0.4-0.6 mm d^{-1}. Despite the higher water use of the poplar-pasture association, soil water in the superficial soil stratum was higher, or similar to, that of the open pasture.

A time-driven mathematical model was used to set a zero offset, adjust anomalous values and describe simultaneous sap velocity time courses of trees. The model shows that daylight sap flow velocities can be represented efficiently with a Beta function model ($R^2 > 0.98$) and differences in the parameters representing the initiation, duration and conformation of the sap velocity can be tested statistically to discern tree transpiration differences during the day.

It was concluded that widely spaced mature poplars influenced rainfall partitioning and prevented the soil from getting wet within the tree crown domain. Tree shading resulted in lower pasture evapotranspiration under the trees.

3.2 Introduction

Widely spaced poplars (*Populus spp.)* have been planted extensively in soil-erosion-prone hills to increase soil stability by decreasing soil wetness (Wilkinson 1996). New Zealand work on spaced trees has been restricted to the effects of individual, young deciduous trees on understorey production (Miller et al. 1996) and erosion control (Hawley & Dymond 1988). However, little is known about the effects of poplars on water use on how much of the contribution to erosion control can be attributed to their capacity to intercept and reduce effective rainfall, dry out the land or increase soil strength (NWS-CO 1983, Hicks 1995). This Chapter examines the differences in rainfall partitioning in a mature poplar-pasture and open pasture systems in hill country and tests the hypothesis of higher water use in poplar pasture systems.

Direct determination of tree transpiration is of particular interest where trees are only part of the vegetative cover of a catchment. Most studies on tree water use have been restricted to flatland forests (Kelliher et al. 1993) or agroforests (Miller et al. 1998). In New Zealand hill conditions, only indirect measurements have been used, including the difference between rainfall and water yield in watershed studies (Pearce & Rowe 1979) or gas exchange at the branch level (Benecke et al. 1977). The heat pulse technique (HP) has been used to independently measure transpirational water loss from branches, roots or tree canopies. Sampling at several depths in the sapwood is usually necessary to characterise the sap velocity (v_c) profile in large trees (Edwards and Booker, 1984). Nevertheless, the HP has problems related to non zero calibration (Hogg & Hurdle 1997) and the occurrence of erratic sensor response when v_c reaches a magnitude < 0.01 mm s^{-1} (Becker 1998). Calibration can be obtained assuming that zero sap flow occurs at the minimum value of the mean (Hogg & Hurdle 1997) or median of sap flux density (Becker 1998). The single hypostomatous leaf model (Monteith et al. 1991) also can be used to correct HP estimates of tree transpiration. However, the instrumentation must account for changing stomatal conductance with canopy depth (Hickley et al. 1994) and can disagree from sap flow close to zero during morning hours, probably because of dew evaporation (Granier et al. 1996).

Sap flow or v_c of trees has been presented in the literature as graphical time courses and daily means have been used for statistical comparisons. However, using daily means overlooks important information on the time course of transpirational activity of individual trees exposed to dissimilar illumination during the day resulting from aspect, tree position on the hillslope and crown dominance. A second objective was to use the results from HP monitoring to develop a simple model to assist in the calibration and in the interpretation of the time course of transpirational activity of individual trees under near ideal meteorological conditions (no rainfall and very few clouds). In particular, the model was also used to calibrate the zero offset and estimate v_c values during the morning that did not conform to the sap velocity trend during the day.

3.3 Materials and methods

3.3.1 Site description

The study was conducted in a mature poplar (*Populus deltoides* clone I78)-pasture area (PP) sited on a commercial livestock farm in the Pohangina Valley (latitude 40°08' S, longitude 175°53' E, 200-250 m above sea level). The site was denominated Pohangina Hill 1. The trees were planted circa 1967 on a northwest facing hill with a 20-25° slope. Mean tree height was 30 m, projected crown diameter was 14.9 m ± 0.7 (mean ± standard error of the mean) and the canopy closure ratio was 66%. The 3.5 ha hill area had unevenly spaced (mean of 16.4 m ± 0.4 spacing, or 37.2 stems/ha). Basal area was 14.5 m^2 ha ± 0.3 and diameter at breast height (DBH) was 0.7 m ± 0.02. The understorey was dominated by browntop (*Agrostis capillaris*) in a mixture of temperate perennial grasses (66% ± 13) and legumes (20 % ± 11, see section 5.4.1.12). An area of open pasture (OP) with similar pasture characteristics adjacent to the PP area was used for comparison.

Soils were ultisols that comprise greywacke sandstones and argillite (Rijkse 1977). Soils in the OP were classified as Orthic Brown Soils and in the PP, as Mottled Orthic Recent Soil (Hewitt 1993). Although both soils had the same texture and macropore function in the 0-150 mm soil stratum, soil in the OP was characterised by abundant sub rounded greywacke stones below 150 mm soil depth (see section 4.4.2.4 and Appendix II). Differences between the OP and PP soil profiles are the result of soil erosion. Differences between the OP and PP soil profiles are the result of soil erosion. Grazing stock were removed from the paddock on 31 October 1996. Pasture cover dry matter (DM) on 25 October was higher ($P<0.01$, n=12) in the PP (1212 ± 46 kg DM ha^{-1}) than in the OP (1013 ± 31 kg DM ha^{-1}, see section 5.4.9.1).

3.3.2 Rainfall partitioning

Measurements of the fate of precipitation were made for 18 consecutive spring days starting on 5 November 1996 for both the PP and OP areas. Spring is the most important season for pasture growth in terms of yield and quality. However, in the PP area the poplars had a fully developed canopy. Assessment of the water use and partitioning at this time of the year would be representative of high water use and the potential of poplars to dry out the soil. Because the OP area lacked an overstorey component, the methodology differed from the PP. Budget and equipment availability limited the extent of the study.

3.3.2.1 Open pasture methods and modelling

Four sampling positions were selected within the OP and away from trees of the PP area. Positions in OP were selected according to ease of installation of the equipment given the stoneyness of the soil. Positions in the OP were in a downhill zigzag transect. For the OP area, equation (1) represented a simple soil water balance describing the partitioning of precipitation (*P*) between evapotranspiration (*ET*), drainage (*D*) and the change in water stored within the soil stratum ($\Delta\theta$) for a time (*t*) interval of one day.

$$P = ET + D + \Delta\theta \tag{1}$$

The $\Delta\theta$ was monitored using time domain reflectometry (TDR, Soilmoisture Co. USA) in the 0-300 mm soil stratum. Probes of 150, 300 and 500 mm length were used (Parchomchuki et al. 1997). By using different probe lengths, water content of intermediate profiles was constructed at steps equal to the differences in probe length (Zegelin et al. 1992). Estimates for θ at time *t* at *z* soil strata of 150-300 and 300-500 mm were obtained according to equation (2). Three sets of probes were installed at all four sampling points. Probes within a set were inserted in the soil 300 - 600 mm apart. Sets of probes were positioned at 1.5 to 3.5 m from each set and around a mini-lysimeter installation. Measurements were made every day at approximately the same hour of the day. Probe sets remained in place for the duration of the study.

$$\theta_{t_{z_{ii}} - t_{z_i}} = \frac{\left(\theta_{t_{z_{ii}}} \times \omega_{z_{ii}}\right) - \left(\theta_{t_{z_i}} \times \omega_{z_i}\right)}{\omega_{z_{ii} - z_i}} \tag{2}$$

where ω was the total soil volume at the *z* stratum to depth *ii* and *i*, given *i* < *ii*.

Parameter *D* was measured with one mini-lysimeter per sampling point. Mini-lysimeters 150 mm in diameter (∅) and 300 mm long were made of PVC cylinders according to Sakadevan et al. (1994). Mini-lysimeters, which were installed by 15th September 1996, were flushed and checked for adequate operation. Vegetation was allowed to grow inside the intact soil core of each mini-lysimeter and remained under the prevailing grazing conditions of the area at all times. The volume of effluent collected was converted to a land area basis to provide an estimation of *D* (mm d^{-1}).

Parameter *P* was measured with one standard rain gauge levelled and with the opening at 300 mm above ground. Three transects of five, one-litre pots (inner ∅ 109 mm) were used to collect rainfall at each sampling point. Transects were approximately 6 m in length. The plastic pots were contained within a bigger pot half filled with soil to provide stability against wind. A small amount of diesel oil was placed in all collecting containers to repel insects and possums and prevent water evaporation of the collected volume. The regression between the standard rain gauge and the pots was used to validate data collection. The volume of rainfall collected every day was converted to a land area basis to estimate P (mm d^{-1}).

3.3.2.2 Poplar-pasture methods and modelling

Four sampling points were selected within the PP area according to the following criteria. Only those trees within one standard deviation of the mean DBH and without flaws below 1.8m of height were indexed in the study. Selected trees were surrounded by other trees to avoid edge effects. From 25 suitable trees, four trees were selected as representative individuals for observation in a zigzag downhill transect. Tree 9 and 73 were in the lower part of the hill and tree 11 and 14 in the mid slope. All measurements for the soil water balance were related to the position of the selected trees. For this poplar-pasture association, the water balance was represented by equation (3) to describe the partitioning between tree transpiration (T), tree canopy interception (I), understorey evapotranspiration (ET_u) and drainage (D) from precipitation (P).

$$P = T + I + D + ET_u + \Delta\theta \tag{3}$$

The T parameter was estimated from the tree sap flow (Q) measured by HP technique (Edwards & Warwick 1984) at the four trees simultaneously from 1 November to 11 December 1996. Records of heat pulse velocity (v_h) were made every 20-minutes from four sets of heat probes and thermistors inserted at 5, 10, 20 and 40 mm below the cambium at 1-m height, around each tree. Insertion of the probes was randomly allocated to four quadrants around the tree circumference. The entire assembly was wrapped in aluminium foil to maintain thermal homogeneity. A radial increment core sample of each tree and quadrant was obtained after the measurement period to determine the conducting wood area and tree age. The inner boundary between heartwood and sapwood was determined by colour. Heartwood was identified by a dark brown colour and sapwood by a light brown colour (Zimmermann 1983). The outer boundary between the sapwood and the cambium was recognised by texture when these two structures separated spontaneously. Volume fractions of wood and water were calculated by Archimedes' principle (Edwards & Warwick 1984). Values of sap flow calculated at each probe depth were considered representative of a ring of sapwood with limits defined by the midpoint between successive probe depths, or by the interface with the cambium or the heartwood (Edwards & Booker, 1984). The HP8000 software (CSIRO, Australia-HortResearch, New Zealand) was used to correct for wounding (Swanson & Whitfield 1981) and calculate the sap velocity (v_c). An estimate of Q was made as the sum of these partial areas multiplied by their associated sap flows. The volume of transpiration per day per tree was converted to a land area basis based on projected tree crown area (Q_c). Tree transpiration to the stand level was scaled up using DBH or the percent of projected crown area and total area exploited by the tree. Only data collected between 0720 and 2220 hours were used for Q integration, because low sap velocities are difficult to distinguish from zero flow (Becker 1998). Nevertheless, calibration of the zero offset and erratic values for v_c were estimated with a Beta function model by simultaneous modelling of a sap velocity basal activity at four sapwood depths (Guevara-Escobar et al. 1997) using 24 hour data. Reference to time was made in New Zealand standard time (NZSTD) being equivalent to Universal Time +1200 hours.

Parameter I of equation (3) was obtained by difference between the measured P at the OP area and the throughfall (Th) at the PP area. Th was measured in a similar manner to P on the OP area. One standard raingauge levelled and with the collecting opening at 300 mm above ground was positioned under the tree canopy. Three transects of five, one-litre pots were randomly arranged around the stem of each of the four trees to measure throughfall. Transects had a length of 6 m and were under the tree crown. Procedures were similar to the measurement of P in the OP area.

Measurement of parameter D and $\Delta\theta$ in the PP area was instrumented in the same way as in the OP area. One lysimeter was installed per tree, but there were only three working mini-lysimeters. The mini-lysimeters were installed approximately 2 m from the trunk base. This made allowed the installation of TDR probes close to the lysimeter and in a similar position of undisturbed soil to that of permanent TDR probes installed in other trees at half the distance between the tree trunk and the canopy edge (see section 5.3.1.2.2). The TDR probes were installed in a similar way as in the OP. Sets of probes were randomly positioned at an average of 3.4 m away from the base of the tree trunk. All TDR sets remained in place during the study.

3.3.2.3 Assumptions

In the OP area parameter ET represents water use occurring in the 0-300 mm soil stratum and was not totally representative of the pasture evapotranspiration. Parameter ET_u represents water use occurring in the 0-300 mm soil stratum only and it was a compound contribution of the pasture and poplar vegetation. Infiltration was equal to rainfall, and surface run-off was negligible at this time of the year (D.J. Barker, personal communication). Because of the technical difficulties in measuring herbage rainfall interception, this was accounted for in ET, ET_u or D.

In the PP area, stem flow (S) was regarded as negligible according to the function S=0.027 P -0.14 (Helvey & Patric 1965).

3.3.3 Beta function model

The Beta function model parameterised temporal variations of sap velocity under near ideal meteorological conditions (no rainfall, very few clouds) and assisted the statistical inference of tree transpiration relations. Temporal transpiration patterns of the trees were compared based on parameters that characterise the main features of v_c during daylight. The parameters of the function were incorporated to represent the asymmetrical distribution of v_c during the day, flow initiation and cessation. Because v_c was measured at several depths in the sapwood, parameters for each depth described radial variation in the axial conductivity. The Beta function (Mood et al. 1974) is a three-parameter function in various forms, used to model phenomena defined over a finite interval $a < x < b$. The Beta function has a wide variety of shapes and theoretical forms have been presented by Yin (1995). This non-linear model can be expressed as:

$$y = \alpha(a - x)^{\beta}(x - b)^{\beta-\gamma} \tag{4}$$

often a and b are scaled to 1 and 0, respectively, α is an amplitude (scale) parameter, and β and γ are shape parameters. Low values (less than 5) of β indicate flatness, whereas high values indicate a sharp peak. Parameter γ is a skewness (or symmetry) parameter, zero indicating symmetry.

Common parameters for β and γ were used to describe the non-linear model shape of all strata. The sap velocity at the four depths was denoted by the subscript i, allowing for the specification of simultaneous fits of particular parameters at each depth along with common parameters. Parameter a was represented as $s+l$, where s is the commencement of daytime v_c activity, $b = s$ and l the duration of daytime v_c activity. Parameter α_i was used to describe the amplitude and k is the baseline activity. All the parameters were incorporated as follows:

$$v_c = k_i + \alpha_i(s + l - t)^{\beta}(t - s)^{\beta-\gamma} \tag{5}$$

for each probe depth i=1...4, regarding each 24 hour period as time t=0...1, and for each tree.

3.3.4 Other measurements

One Stevenson screen was installed at a representative point in each area to house a maximum and minimum air thermometer at 1.5 m from the ground. Soil temperature was recorded at 100 mm depth at each sampling point. Daily records of air and soil temperature were kept during the soil water balance assessment. Photosynthetically active radiation (PAR) was measured under the tree canopy with one Licor L-1000 data logger coupled to a quantum sensor at 300 mm above the soil surface. Maximum and minimum radiation values were recorded at 20-min intervals. A reference PAR value for OP was obtained from a nearby experiment (Ross Edwards personal communication). Leaf area index (LAI) and CCR of each of the instrumented trees were determined at a later date. LAI was measured at four points half the distance between the canopy edge and the tree trunk at each of the HP instrumented trees with a Licor LAI-2000 canopy analyser. CCR for each tree was determined using digital image analysis. The proportion of tree canopy was reported as a percentage of the total area in the picture, which was considered a reasonable estimate of the projected tree canopy in the ground surface. Digital photographs were taken during December and January 1997 facing vertically towards the poplar canopy with Kodak digital Science DC-50 camera (Eastman Kodak Co. 1995) under overcast conditions. Fifteen to twenty non-overlapped pictures were digitally taken to represent each tree's canopy and the gap area with the neighbouring trees. For each tree the CCR was calculated by quantifying the pixels of the tree canopy and dividing it by the total number of pixels in the image (see section 5.3.1.2.4). In addition, the area of canopy gaps with Ø > 1 m was calculated to represent the canopy gap area (CGA) between trees.

3.3.5 Statistical analysis

Rainfall and throughfall data were subjected to regression analysis to test consistency with the standard raingauges. Analysis of tree canopy effect on throughfall was based on a factorial design, the factors being day of rain event, tree and distance from the tree trunk, with distinction for high and low intensity rain events (Steel & Torrie 1980). Linear models were analysed with the GLM procedure (SAS Institute 1996). All linear models were tested for residual normality and homogeneity of variance using the residual analysis and regression diagnostics option of Minitab 10.51 package (Minitab Inc. 1995). Non-linear models (Appendix III) were fitted using the SigmaPlot 4.0 curve fitter (Jandel 1995). Whenever possible, the simplest model was assumed. The significance level was set at α=0.05. Differences between trees and days for the parameters of Beta function curve were tested by least squares analysis of variance (García-Muñiz et al. 1998) using the GLM procedure (SAS Institute 1996).

The hypothesis of no time effect on θ and no difference between the TDR installation sets within the sampling position was explored using the GLM and MIXED (SAS Institute 1996). The repeated measures models were examined with different covariance matrix structures (autoregressive, compound symmetry and first order unstructured). The likelihood ratio test (LRT) was used to test against a null model covariance structure (identity covariance matrix). Models were compared using the difference of the –2 log likelihood values of two models with two degrees of freedom χ^2 distribution (SAS Institute 1996).

3.4 Results

3.4.1 Rainfall

Total rainfall recorded with the standard raingauge for OP was 77.4 mm. Rainfall higher than 1 mm occurred on 9 days, four events ranged from 13.0 to 15.5 mm d^{-1} (Figure 3.1). Agreement between rainfall measured with the standard raingauge ($P_{standard}$) and the pots (P_{pots}) was good (r=0.996 ± 0.004), although it was affected by two low correlation coefficients (0.81 and 0.86) caused by missing values. The regressed linear equations for $P_{pots} = \beta_0 + \beta_1 P_{standard}$ were significant (P<0.01) for each transect sub-sample. The mean value for β_1 was 0.98 ± 0.004 with r^2 of 0.996 ± 0.0003 (n=60). The parameter β_0 was not different from an intercept equal to zero for all the equations. Based on this evidence, the differences between $P_{standard}$ and P_{pots} were attributed to random variation and no further adjustment was considered. Total rainfall recorded as P_{pots} was 72.5 ± 0.9 mm for the period and assumed to be representative of P.

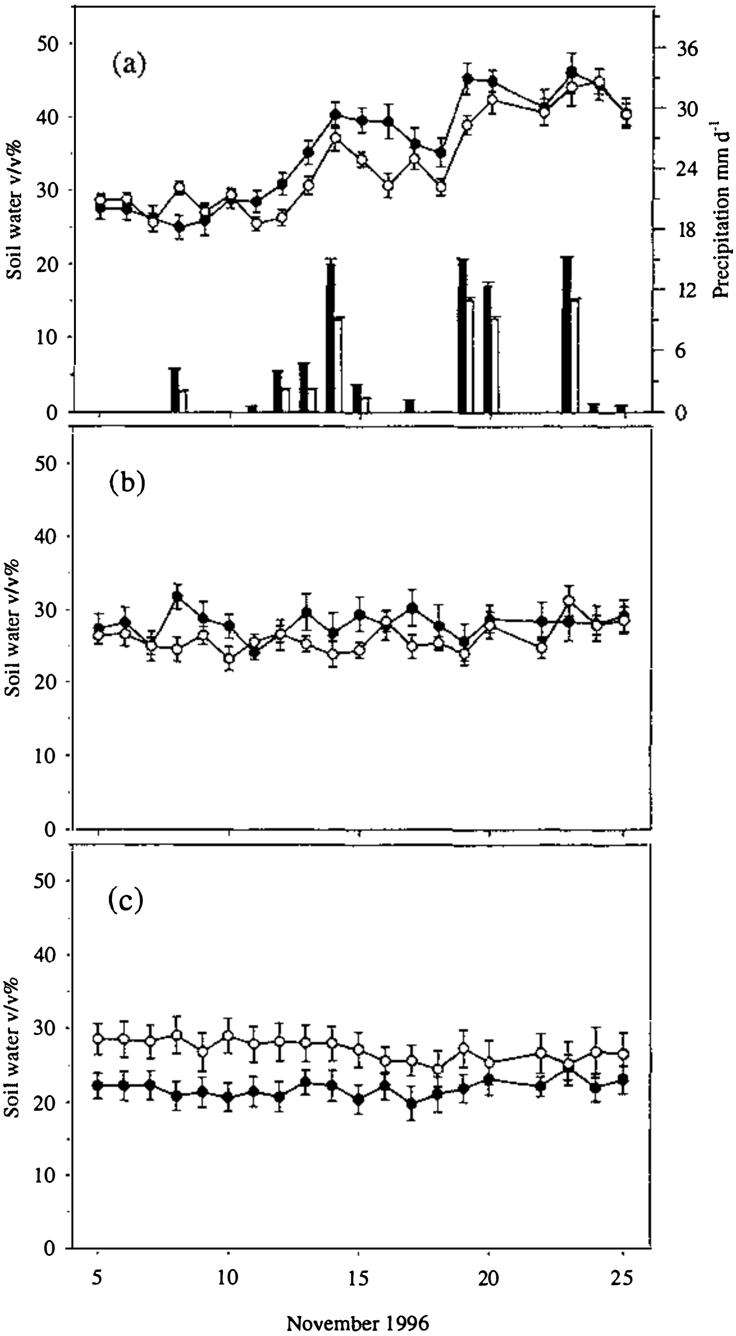

Figure 3.1. Rainfall (black bar), throughfall (white bar) and volumetric soil water in the open pasture (OP, •) and poplar pasture (PP, o) at 0-150 (a), 150-300 (b) and 300-500 mm (c) soil strata during November 1996. Bars represent the standard error of the mean.

Total drainage recorded as D for OP was 4.2 ± 1.6 mm for the period. Drainage occurred only during the four rain events with P > 12.4 mm d^{-1}. No drainage was recorded during rain events with $P < 4.6$ mm d^{-1}. D was slightly correlated with P (r=0.36) but P did not explain the variability of D, because of the small number of lysimeters used and the small number and size of each drainage event. Lagging the rainfall by one day did not show any improvement in the relationship.

3.4.2 Soil moisture in the open pasture

Except for one TDR probe at 0-150 mm soil stratum, open pasture θ at the different sampling points followed a similar trend. A consistent increase of θ with the occurrence of rainfall was observed (Figure 3.1). θ variance was not constant over time at the 0-150 mm soil stratum, but at deeper soil strata variance did not depend on changes in the mean θ. For the 0-150 mm soil stratum the mean θ for the period was 34.6 ± 0.6 % v/v.

Derivation of θ at the intermediate soil strata 150-300 and 300-500 mm using equation (2) showed that rainfall was insufficient to evenly increase soil water at all strata. The mean θ for the period was 28.1 ± 0.5 and 22.2 ± 0.4 % v/v for 150-300 and 300-500 mm soil strata, respectively. Repeated measures analysis with a first order autoregressive covariance matrix structure showed no significant t effect at the 150-300 and 300-500 mm soil strata indicating that water leaching into the 300-500 mm soil stratum was negligible and that soil water change mainly occurred in the 0-150 mm soil stratum. Nevertheless, the complete 0-300 mm soil stratum was used to calculate $\Delta\theta$and allow the incorporation of the D parameter. Differences between TDR sets within a sampling position were not significant.

The accumulated $\Delta\theta$ at 0-300mm soil stratum for the period was 29.2 ± 1.8 mm indicating θ net accumulation. Figure 3.2 shows the linear relationship (r^2=0.68, P<0.01) for $\Delta\theta = \beta_0 + \beta_1 P$, where β_0 was not different from 0 and β_1 was 0.7. Because $\Delta\theta$ was also dependant on ET and drainage, the relationship with rainfall was not strong. ET from the 0-300 mm soil stratum for OP was 39.1 mm for the period and an ET rate of 2.2 mm d^{-1}.

3.4.3 Throughfall

Total throughfall recorded with the standard raingauge for PP was 52.2 mm and occurred in eight main events greater than 1 mm d^{-1}. Rain collected with pots (Th) showed characteristic variation. According to intensity, two groups of Th events were identified, high (H) and low (L). For H and L events, Th values of 10.0 ± 1.9 and 1.9 ± 0.4 mm d^{-1} were recorded, respectively. The Th values were consistent across H and L events for all 4 measured trees and increased with increasing distance from the tree trunk (Table 3.1). Because the standard rain gauge could not account for the variability identified in Th, it was assumed to be a good estimator of throughfall.

The relationship between *Th* and *P* showed good agreement when mean values for each main rain event were represented by $Th=\beta_0+\beta_1 P$ ($r^2=0.98$ $\beta_0=-0.92$, $\beta_1=0.76$, $P<0.01$). β_0 was used to approximate the tree canopy water storage capacity, being 0.92 mm (Kelliher et al 1992b). β_1 indicated the rate of *Th* after storage capacity was exceeded. Total *Th* was 47.7 mm and *I* was estimated as 24.8 mm for the period. Total drainage recorded as *D* for PP was 1.9 ± 1.7 mm for the period and occurred during the same days as OP.

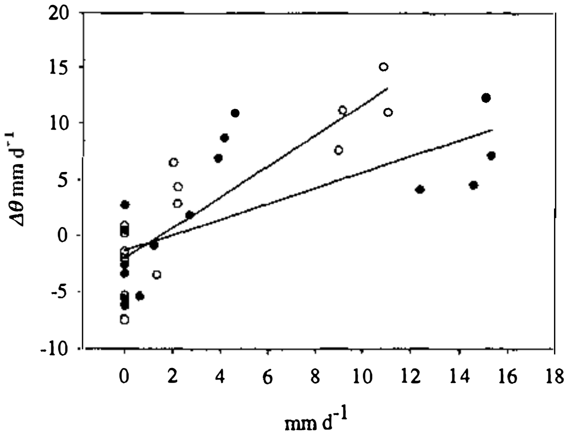

Figure 3.2. Relationship between values of soil water change ($\Delta\theta$) in the 0-300 mm soil stratum and rainfall (*P*, •) for the OP area and throughfall (*Th*, o) for the PP area. The lines represent the corresponding linear model.

Table 3.1. Consistency of *Th* values during high and low rainfall events under a poplar canopy according to measured tree and closeness to the tree trunk.

	High		Low	
Tree No.	Mean	SEM[1]	Mean	SEM
11	10.5a[2]	0.24	2.0a	0.06
14	10.4a	0.24	2.1a	0.07
9	9.9a	0.24	1.9a	0.07
73	9.1a	0.24	1.8b	0.05
Closeness[3]				
1	9.5a	0.27	1.6a	0.07
2	9.5a	0.27	1.7a	0.07
3	10.2ab	0.27	1.9b	0.06
4	10.4b	0.27	2.2c	0.07
5	10.4b	0.27	2.4d	0.07

[1] Pooled standard error of the mean.

[2] Within high or low intensity rain events, means with same letter were not significantly different ($P<0.05$).

[3] Relative position to the tree stem, 1 closer and 5 farther.

3.4.4 Soil moisture under poplar trees

The OP and PP had a similar θ at the start and end of the monitoring period at all three soil strata ($P>0.05$). θ for PP increased with rainfall mainly in the 0-150 mm soil stratum, as in the OP area (Figure 3.1), although variation was greater between the PP positions. Mean θ at the 0-150 mm soil stratum was 32.5 ± 0.5 % v/v but θ variance was not constant over time. As in the OP area, variance was constant at the other strata. The increased variance of θ at the 0-150 mm soil stratum for both OP and PP was related to the occurrence of rainfall events. $\Delta\theta$ totalled 31.0 ± 4.8 mm for the period, but θ accumulation was not significantly different from the OP ($P>0.05$). The linear relation ($r^2=0.87$, $P<0.01$) for $\Delta\theta=\beta_0+\beta_1 Th$ is shown in Figure 3.2, where $\beta_0=-2.0$ and $\beta_1=1.37$. However, the relation was an artefact caused by the small number of throughfall events ($n=8$), 4 about 2 mm d^{-1} and 4 about 9 to 10 mm d^{-1}, a higher number of throughfall events were needed to characterise $\Delta\theta$ based on *Th*. The mean θ for the intermediate strata (150-300 and 300-500 mm) was 25.8 ± 0.4 % v/v and 27.2 ± 0.5 % v/v respectively. The obtained ET_u from the 0-300 mm soil stratum was 14.8 mm for the period or 0.82 mm d^{-1}. The ET_u was a combined contribution of pasture and tree water use.

3.4.5 Poplar transpiration

The observation period provided a variety of meteorological conditions. Development of the v_c Beta function model was made with these data. Sunrise and sunset hours were 0518 and 1914 for 1 November 1996. However, not all the trees initiated sap flow activity at the same time. Figure 3.3 shows the diurnal evolution of v_c on a day characterised by clear skies and low wind speed. Variation of v_c between trees and probe depth (*l*) was by an order of magnitude. For any given day, v_c increased well after sunrise, reached a peak at noon and then declined to low rates at night. Hill aspect and the twilight hours modified and delayed start in activity. During days with variable cloudiness, substantial variation in radiation caused erratic patterns of v_c and consequently poor fits of the beta function model.

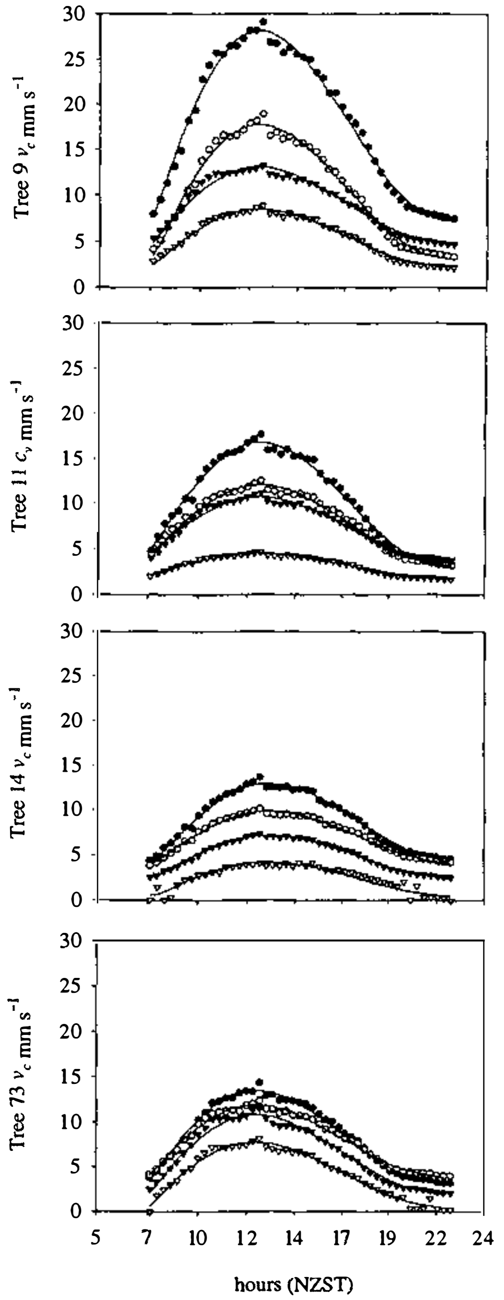

Figure 3.3. Daily pattern of sap velocity (v_c) at four depths (•5, ο10, ▾20 and ▿40 mm) in the sapwood on 25-11-96 and the corresponding Beta function model (—).

On a daily basis, good agreement was found between the observed v_c time course and the nonlinear model, R^2 ranged from 0.932 to 0.997. The model demonstrated good consistency across trees during good weather conditions but some trees consistently obtained better fits. Rainy or variable cloudiness resulted in flat-top or incomplete v_c time courses not in accordance with the Beta function. Although the HP technique showed consistent performance during most of the time, occasional perturbations in the measured v_c early in the morning and late at night originated a number of data outliers that added up to a difference of ±10 l

Table 3.2. Parameter k estimates of the Beta function sap velocity (v_c) model for four trees at various depths in the sapwood of poplars from 5-11-1996 to 9-12-1996.

	probe depth into the sapwood (mm)							
	5		10		20		40	
Tree	Mean	SD[1]	Mean	SD	Mean	SD	Mean	SD
				k (mm s^{-1})				
9	4.858a[2]	1.707	1.303b	1.233	4.428d	0.662	1.597b	1.381
11	1.552b	1.098	2.515b	0.694	2.368b	1.166	1.171b	1.089
14	2.428c	0.897	3.159a	0.535	1.738a	0.462	0.457a	0.472
73	0.165d	0.220	0.523c	0.819	3.101c	0.545	2.202c	1.439

[1] Standard deviation.

[2] Within a probe depth, figures with same letter, were not significantly different ($P>0.05$).

Table 3.3. Beta function parameters common to four sapwood depths (5, 10, 20 and 40 mm) used to model sap velocity (v_c) of poplars from 5-11-1996 to 9-12-1996.

Tree #	α[1]	β	γ	l	s
14	31440a[2]	3.22a	1.23c	0.71a	0.29b
11	22961a	3.27a	-0.41a	0.78a	0.17a
73	8593a	3.31a	1.08cb	0.69a	0.28b
9	71645b	3.48a	0.23ab	0.76a	0.21ab

[1] Parameter was estimated at each sapwood depth but for clarity the mean of all depths is only presented.

[2] Means with same letter were not significantly different ($P>0.05$).

tree d^{-1} when estimating Q values. Consequently, v_c outlier values were adjusted with the corresponding model for each tree and day. To obtain a zero calibration in the HP, a 95% confidence for a $k \neq 0$ offset was constructed based on the two standard deviations of the normally distributed k parameter for each probe depth and tree (Table 3.2). If 0 was within the 95% confidence interval, then k was the zero. Thus, for tree 9 the offset was 3.4, 1,3, 1.4, 2.5 (0) mm s^{-1} for v_c at 5, 10, 20 and 40 mm in the sapwood.

Differences in the model parameter values were identified among trees when applying analysis of variance (Table 3.2 and 3.3). Most of the differences were attributed to a higher activity ($P<0.05$) of tree number 9, which had higher v_c values, although this tree was not the biggest in any measured trait (Table 3.4). Parameter estimates were significantly different between days. Nevertheless, consecutive days tended to present no significant differences.

A summary of various tree characteristics relating to the calculation and interpretation of sap flow is shown in Table 3.4. Mean daily water use of trees measured as Q for the period was 188.5 ±7.7 l d^{-1}. Measured Q values differed by an order of magnitude, bigger trees showed higher Q values. Maximum Q was registered for tree number 14 with 417.0 l d^{-1} (Table 3.4). Mean Q_c was 1.23 ± 0.1 mm d^{-1}. Q was positively correlated with sapwood area, DBH, projected crown area and crown volume (0.86, 0.93, 0.72 and 0.89, respectively) but the relation

Table 3.4. Characteristics and sap flow of poplar trees sampled in November 1996.

Tree #	DBH[c]	Projected crown	Crown volume[d]	Crown LAI[e]	Sapwood fractions		Sapwood area	Q	Q_c	Max[a] Q	Min[b] Q
	m	m^2	m^3		water	wood	m^2	($l\ d^{-1}$)	($mm\ d^{-1}$)	($l\ d^{-1}$)	($l\ d^{-1}$)
11	0.63	97	261.5	8.0	32%	31%	0.1464	119.4	1.23	162.2	95.4
14	0.79	275	441.3	6.2	32%	29%	0.2147	215.1	0.78	417.0	136.3
9	0.72	134	358.5	7.3	29%	30%	0.1699	195.9	1.46	244.5	111.6
73	0.70	131	324.8	7.5	32%	32%	0.1975	190.0	1.45	291.3	109.4
Mean	0.71	159.2	346.5	7.3	31%	30%	0.1821	180.1	1.23	278.6	113.2
SE[f]	0.03	39.5	37.4	0.3	1%	1%	0.0154	20.9	0.16	53.3	8.5

[a] Maximum sap flow rate observed during the period (overcast high wind run).

[b] Minimum sap flow rate observed during the period (overcast calm).

[c] Diameter at breast height (1.30m) on the uphill side of the tree.

[d] Crown volume modelled after Wilkinson (1995).

[e] Leaf area index for the projected crown.

[f] Standard error of the mean.

was negative with LAI (-0.84). Only trees 11 and 14 had a high correlation (0.92) in their 20-minute sap flow. Tree 11 had a 0.60 correlation with trees 9 and 73 and tree 73 with 14 (0.60). Tree 73 also was poorly correlated with tree 9 (0.29). Trees 9 and 73 had very similar water use by leaf area and higher than trees 11 and 14 (0.20, 0.19, 0.15 and 0.13 l m^2, respectively).

DBH has been used as a representative flux scalar for water use (Hatton et al 1995). The best description of Q as function of poplar DBH was obtained with a classic asymptotic model:

$$Q=\frac{218.8}{1+e^{-\left(\frac{DBH-0.62}{0.04}\right)}} \qquad (6)$$

Tree water use at the stand level (T) was calculated as 0.63± 0.1 mm d^{-1}. Although the model offered a good fit (R=0.98), extrapolation to trees with DBH <0.63 m caused a sharp drop in predicted Q. This was a consequence of the small number of observations, the fact that all the sap flow observations were well in the upper part of the asymptote and consequently an arbitrary inflexion point (0.5 of maximum DBH) and origin (0). For DBH to be an effective scalar, a higher number of instrumented trees would be required (Vertessy et al. 1997). An alternative scalar to DBH was the projected crown area and CGA, which is less sensitive to individual tree variation and provides a good indicator of the domain exploited by trees. CGA for the instrumented trees and their neighbours was 105 m^2. The proportion of gap area that corresponded to a single tree was calculated as the single tree gap area (STGA):

$$STGA=\frac{\frac{CGA}{2}}{projected\ crown\ area+\frac{CGA}{2}} \qquad (7)$$

Estimation of T by multiplying Q_c by 1-STGA (0.75) yielded 0.92± 0.12 mm d^{-1} or 16.7 mm for the period.

3.4.6 Microclimate measurements

No differences were found between OP and PP for maximum (15.7 and 15.5 °C, respectively) and minimum (6.7 and 8.0 °C, respectively) air temperatures. However, soil temperature was higher ($P<0.01$) in OP (14.1 ± 0.1 °C) than in PP (12.0 ± 0.1 °C) during the morning. Average photosynthetically active radiation varied by more than an order of magnitude between the OP and PP areas (Figure 3.4).

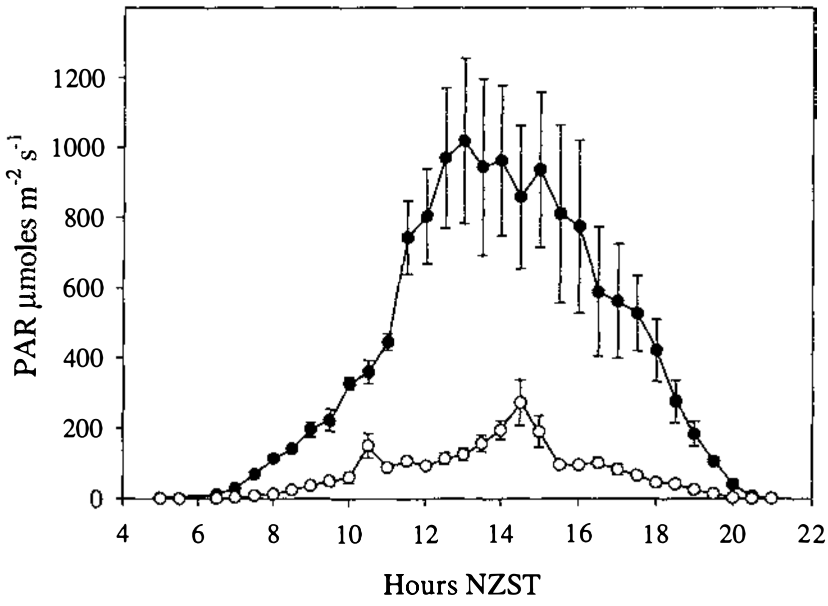

Figure 3.4. Average time courses of photosynthetically active radiation (PAR) during November 1996 at Pohangina Valley. Symbols represent 20 min average values for the open pasture (OP, •) and the poplar-pasture (PP, o) areas. Line bars represent the standard error of the mean.

3.5 Discussion

3.5.1 Rainfall partitioning

Rainfall interception was the most important component from rainfall partitioning in the PP system, along with topsoil ET_u (0-300 mm soil stratum) accounted for 39.6 mm, a very similar amount to the topsoil *ET* from the OP system (Figure 3.5). Both systems had similar water change in the topsoil although the PP topsoil received less precipitation. Drainage was similar between the OP and PP and small in relation to the total rainfall.

With the exception of a small loss to drainage, water loss in the 0-300 mm soil stratum was attributed to evapotranspiration and most of the infiltrated water was retained within the 0-150 mm soil stratum. Water movement from the 0-150 into the 150-300 mm soil stratum possibly was modified by different organic matter content in the PP and by gravel in the OP (see section 5.5.4). Water movement in these sandy loam soils is driven by the high hydraulic conductivity of big pores at or near saturation, while very little capillary movement occurs at lower matric potentials (dry soil) when hydraulic conductivity decreases. Analysis of soil pore size distribution (see section 4.4.2.4) showed that total porosity was 53.6 and 52.4 m^3 m^3 for the 0-150 mm stratum for the OP and PP. From Figure 3.1 it is clear that soil water content was below 50%.

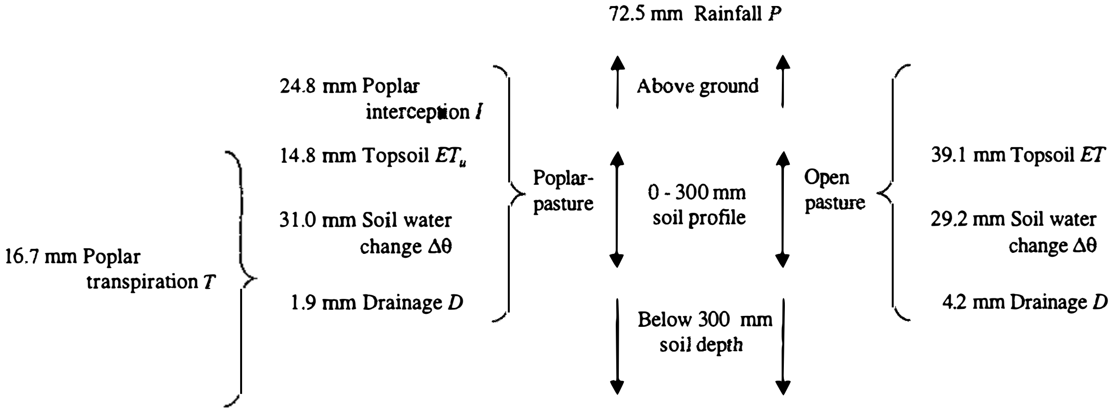

Figure 3.5. Partition of 72.5 mm of rainfall in the open pasture (OP) and poplar-pasture areas (PP). Numbers indicate mm of water per 18 days of study in November 1996. Tree transpiration also is represented but its contribution to soil 0-300 mm *ET* could not be determined.

Saturated flow would start at 52%. It is possible that soil moisture increments in the 150-300 mm soil stratum also originated from instantaneous saturation or preferential flow by cracks from the upper soil stratum. Percolation was greatly reduced and slowed in these unsaturated soils (Hibbert 1976, McLaren & Cameron 1996). Although the water content in the 150-300 mm soil stratum always was lower than 35% and it could store a considerable amount of water available to the plants above a matric potential of -30 kPa.

Topsoil ET_u partitioning from the 0-300 mm soil stratum between the poplar and the pasture understorey was not possible. However, it was hypothesised that pasture water use had a greater contribution to the measured ET_u within the 0-300 mm soil stratum because root biomass decreased exponentially with increasing soil depth (Eastham & Rose 1990). Herbage roots were very superficial and 90% of them were contained in the upper 200 mm in seven pits used to typify the soils of the poplar-pasture area (Alan Palmer personal communication). Barker et al. (1988) determined that 58 and 71% of the root biomass was in the upper 100 mm of sunny and shady aspects of hill pasture, respectively. In the present study, coarse and fine poplar roots were observed to be distributed down to the 1000 mm excavated (Alan Palmer personal communication).

Using the understorey and open pasture DM accumulation rate (26.3 and 15.3kg DM ha^{-1} d^{-1}) a 1.4 mm d^{-1} understorey water use was calculated based on 0.09 mm kg DM ha^{-1} d^{-1} water efficiency rate from the open pasture area. Pasture growing under shade can have higher water use efficiencies (Eastham et al. 1990, Wallace 1996). Fifty percent higher water use efficiency for the understorey (< 0.05 mm kg DM ha^{-1} d^{-1}) could accommodate an ET_u value of 0.82 mm d^{-1}. With these considerations it was assumed that the understorey contributed between 50 and 80% of the ET_u in the 0-300 mm soil stratum.

The poplars evapotranspiration (ET_t, represented by combining T and I (2.3 mm d^{-1}), influenced the water balance to a greater extent than the PP understorey (0.4-0.6 mm d^{-1}). Although ET_t was similar to the ET in the OP area it differed from the OP ET in that I never reached the soil, potentially increasing soil stability.

ET in the OP (2.2 mm d^{-1}) was lower than the combined poplar transpiration, interception and understorey ET_u (2.7 to 3.0 mm d^{-1}). In general, the daily averages of evapotranspiration for the open pasture and poplar-pasture areas were within the boundaries reported in the literature for grassland, broadleaf forested (Kelliher et al. 1993, 1995) and pastoral ecosystems (Parfitt et al. 1985, Ridley et al. 1997).

Poplar water uptake close to the water table could explain why $\Delta\theta$ was small on the poplar-pasture area. The evidence suggests that poplar trees did not compete for water with the pasture understorey when water was plentiful. Indirectly, tree shade resulted in lower soil temperatures and a reduced radiation regime (see section 5.4.1.1 and 5.4.1.2), decreasing understorey evapotranspiration, effectively increasing the efficiency of water use.

The percent of rainfall intercepted by the poplar canopy (34%) was higher than that reported for forestry stands of poplar (26%) in Italy (Tarsia 1980) and radiata pine in New Zealand (19%, Kelliher et al. 1992b) and Chile (20%, Huber et al. 1985). Throughfall from heavy crowned open grown trees usually is 70-75% of gross rainfall as opposed to 80-85% under forest trees

(Helvey & Patric 1965) and varies with gauge distance from the tree trunk to the crown periphery (Stout & MacMahon 1961). The studied poplars have the greatest contribution to intercepted rainfall with low intensity rain events. Although based on a reduced number of observations, the water storage capacity of the poplar canopy (0.92 mm d^{-1}) along with the high LAI (6.2-8.0) could explain the measured interception. If the observed interception is considered to remain constant during the growing season, then about 220 mm yr^{-1} could be intercepted by the tree canopy.

The pattern of *Th* distribution could not be attributed to a stand-edge effect, but it may be a reflection of canopy architecture (Watanabe & Mizutani 1996). Because the mean canopy gap Ø was relatively small (2 m) its effect on *Th* was disregarded. Poplar canopies have a greater canopy depth closer to the stem and consequently water storage capacity will vary according to the distance from the tree stem. However, the small differences found in this study do not explain the decreased occurrence of shallow landslides related to the closeness to *P. nigra* stems reported by Hawley & Dymond (1988) where root interlocking was probably a major factor.

Although *Th* was lower than *P*, the PP and OP topsoil had similar $\Delta\theta$ and θ until the end of the monitoring period, implying that less soil water was used in the PP than in the OP. Animal traffic in silvopastoral environments can provoke changes in soil structure and reduce the infiltration rate of the soil (Bezkorowajnyj *et al.* 1993). However, soil physical properties (see section 4.4.2.4), $\Delta\theta$ and θ in the PP area suggested that animal traffic was not important in the Pohangina Hill 1 site.

The poor relation between *P* or *Th* and *D* not only was attributed to the small number of lysimeters used, but also because the water infiltrated into the soil was mostly withheld in the upper 0-150 mm soil stratum. It is possible that rainfall events of bigger magnitude cause an increase of *D* and would be better related to precipitation.

3.5.2 Sap velocity model

The multiple Beta function model provided a more robust zero offset to calibrate the HP technique than alternative approaches (Hogg & Hurdle 1997, Becker 1998). Because parameter *k* was different between trees and sapwood depth, calibration for each probe was appropriate before integrating sap flow. The high R^2 obtained for the sap velocity Beta function suggested that comparision of the models among trees should reveal differences in the individual trees and sapwood depths, and not from the model.

The Beta functions also provided information to differentiate sap velocity activity of trees that otherwise were considered similar. Trees 9 and 73 had very similar DBH, projected crown area, LAI, daily sap flow and sap flow by leaf area. However, correlation between their 20-minute sap flow activity was poor. The analysis of variance of the Beta function parameters showed that tree 9 had higher basal activity (k) and amplitude (α) at each of the four sapwood depths than tree 73. However, tree 73 had a slightly higher sapwood area and had a tendency for sap velocity activity to start earlier (s, $P<0.1$) and persist for longer (l, $P<0.16$) than tree 9 during the measuring period. Tree 11 had the smallest daily sap flow, but its sap flow by leaf area suggested that this was a very active tree compared with the other trees. In addition, parameters γ, l and s indicated that tree 11 had most of its activity during the morning hours and earlier than tree 14 and 73 but not 9. Visual observation of the social position of trees 9 and 11 suggested that they received sunlight earlier than the other two trees and tree 11 perhaps received more shade after midday. Therefore, tree 11 was able to cope with its transpiration demand better during the morning hours. The evidence suggests that trees with morphologically similar characteristics differ in their water uptake pattern during the day and still result in a very similar daily uptake. The ability to relate the parameters of the beta function to traits of physiological significance and the flexibility in their application signifies an improvement over symmetric models (Howard et al. 1997), discrete-point hypothesis testing (Berbigier et al. 1996, David et al. 1997) or graphical representations (Dunn & Connor 1993, Bréda et al. 1995, Becker 1996). Although this model cannot replace weather driven models, it allowed a more efficient approach to hypothesis testing sap velocity time courses between trees.

3.5.3 Tree water use

Reduced water use by an ageing stand (Dunn and Connor 1993) and transpiration suppression by evaporation of intercepted water (Tolk et al. 1995) may explain why the Q_c values were smaller than values of younger poplars planted at higher tree densities; 4.8 mm d^{-1} by Hinckley et al. (1994) and 3.4 mm d^{-1} by Zhang et al. (1997). However, maximum individual tree water use, 39-51 kg d^{-1} for Hinckley et al. (1994) data, as opposed to the maximum measured Q of 417 l d^{-1} (tree 14) reinforce the importance of tree age and crown development for soil stabilisation, independently of root interlocking (Hicks 1995). Tree 14 had the lowest LAI and only a maximum T of 1.14 mm d^{-1} while the mean of maximum T for the other three was 1.43 mm d^{-1} ± 0.11. During the examined period, tree 14 was transpiring at a mere 51.4 % of the maximum, while the other three trees were at 73%. Rough canopies, as the one found with wide spaced trees would be driven more by the advective component than a smooth canopy and consequently prone to higher transpiration. This has been found in the Spanish Dehesa, where widely spaced oak canopies (40 sph) were more dependant on atmospheric conditions (Infante et al. 1997). Also, poplars have an isohydric behaviour, maintaining a nearly constant daytime leaf water potential at a value which does not depend on soil water status until plants are close to death (Tardieu & Simonneau 1998). In the present study, the maximum rate of poplar transpiration per leaf area (0.25 l m^2 ± 0.02) which was driven mainly by wind compared to calm conditions (0.11 l m^2 ± 0.01) gave an indication of this behaviour. These observations are important for canopy structure and silvicultural management because the typical high wind in New Zealand's environment will favour higher decoupling coefficients according to Jarvis and McNaughton (1986) formulation of stomatal control of transpiration. Tree transpiration and atmospheric demand explains why poplars stagnate in the upper, exposed hill sites while some *Eucalyptus*, being adapted to dry sclerophyllous communities (Specht 1996), thrive (NZMF 1995).

Tree water use in present study gave a good indication of the capability of mature poplars to dry out the soil. If the trees have had a water use of 1.43 mm d^{-1} and all conditions remaining the same, ET_t would be 50.5 mm, ET_u about 10.8 mm (0.6 mm d^{-1}) and $\Delta\theta$ at 0-300 mm would be 11.6 mm when P was 72.5 mm for 18 days. If rainfall is lower $\Delta\theta$ can become negative if the poplars cannot exploit a different soil stratum. This situation is likely to occur for short periods during summer in the Pohangina site or become a critical condition in summer dry areas of the East Coast (Gilchrist et al. 1993).

The water relations corresponded to the tree canopy domain and in this study it was considered to be uniform under the poplar canopy. Tree plantings with different crown architecture or spacing will have various effects. Interception by isolated trees probably will be much smaller and pasture growth and tree roots may be more important than evapotranspiration for erosion control. On the other hand, densely planted trees may have higher interception, but probably the understorey growth will be inhibited by the decrease in light and soil water.

3.6 Conclusion

The tree canopy had a higher evapotranspiration than open pasture in November. Wide spaced-planted poplars at 37 sph intercepted 34.2% of the incoming rainfall. Interception was more important during low rainfall events. Although the poplars studied had similar DBH, the transpiration measured was variable between individual trees. The time course of sap velocity was described with a mathematical model and significant differences were found in its parameters closely related to individual tree characteristics. For the trees studied the model was useful in characterising sap velocity and in the description of daytime activity.

Soil water under the poplars remained constant and at a similar level to that of the open pasture, because evapotranspiration was lower in the superficial soil stratum and compensated for intercepted rainfall by the tree canopy. Results suggested that the understorey had a lower evapotranspiration (0.4-0.6 mm d^{-1}) than herbage in the open pasture (2.40 mm d^{-1}), this was attributed to tree shading. Soil moisture was high during this study, however rainfall was moderate and mostly occurred in small events, and poplars prevented further soil water increase. Probably, rainfall interception by the tree canopy would be smaller with higher precipitation. If that is the case, soil moisture could increase and the soil binding characteristics of the poplar root system would be more important for land stability. On the other hand, if meteorological conditions impose a higher transpiration rate on the poplars then trees would be more valuable; particularly bigger trees, although at some stage they will compete with pasture for soil moisture. Further study of pastoral ecosystems with land conservation trees requires more detailed examination of soil water and under a wider range of seasonal rainfall conditions. Water uptake and interception were important mechanisms in the present study, but definition of the precise site of water extraction of individual trees and/or the stand is needed for a more complete understanding.

3.7 References

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4. Soil properties of a poplar-pasture system in a hill environment

4.1 Summary

The impact of poplar-pasture system on hill soils was compared with hill soils under pasture. One site, Pohangina Hill 1 served as model of the poplar-pasture system. Major findings were measured in other sites to corroborate the initial results. Topsoil samples were collected from three unreplicated sites (Pohangina Hill 1 and 2 and Rongoiti) space planted with mature (>29 years) poplar (*Populus deltoides*) at 37-40 stems/ha (sph) and from a replicated experimental site (Ballantrae) with young (5 year) poplars at 50-100 sph. All sites had pastures dominated by low fertility grass species and were grazed by sheep and cattle. Paired samples from poplar-pasture (PP) and open pasture (OP) were analysed for pH, total N, P and S, organic C and S, and plant available P, K, S, Ca Mg and Na, anion storage capacity, invertebrate populations, soil texture, bulk density (BD), soil aggregate stability, hydraulic conductivity and macro-porosity.

Soil pH was higher, from 0.5 to 1.2 pH units, on the PP, as were exchangeable cations in the upper 75 mm of soil. Soil samples from Pohangina Hill 1 showed that differences found in soil pH and cations in the 0-75 mm stratum were also present at 75-150 and 150-300 mm soil strata. Soil pH in the PP was also higher at an additional six sites with widely spaced poplars (ranging in age from 15-30 years) in the Manawatu, Wanganui and Rangitikei Districts. No difference was found in organic C, total N, P or S, or plant available P or S between the OP and PP areas. From a glasshouse experiment, it was found that topsoil (0-20 mm) from poplar-pasture vegetation was superior in supporting herbage growth, and mineralised tree leaf litter had the potential to increase herbage growth when compared to topsoil from the open pasture. Soil P, K, Ca, Mg were more concentrated in the 0-20 mm in the PP area, but in the 0-75 mm the OP had a higher concentration of the same nutrients. Multiple processes such as throughfall and leaf litter chemistry, reduced N-fixation by legumes, poplar N nutrition, reduced leaching, nutrient cycling and a more efficient nutrient use of poplars might be involved in modifying soil pH and cation accumulation in soil. Some differences in earthworm numbers and biomass were found, with the data from the Pohangina sites suggesting that population dynamics, in addition to mass and number, were different for the OP and PP environments. Despite higher soil pH, Ca and litter substrate, earthworm populations generally were similar or lower in the PP. Hydraulic conductivity was found to be similar, as was macro porosity and water aggregate stability and BD at the Pohangina Hill 1 site. Poplars contributed in the "healing" process after erosion but after 29 years the process was incomplete and the soil of the PP was considered young in origin. Tree leaf litter was identified as a mechanism of nutrient redistribution of potential importance for soil fertility restoration in eroded pastureland. It is possible that poplar planting on the poorly mineralised environment of slip scars may reduce the time of healing.

4.2 Introduction

Soil erosion is common in New Zealand on sedimentary mudstones, siltstones and pumice soils (Kelliher et al. 1995). Most of the slip, slump and gully erosion has been a consequence of forest clearing for pastoral agriculture dating back to European settlement (Trustrum & DeRose 1988). Mass movement and earthflows occur in forested hill country catchments but at a lower frequency (James 1973). Studies of slip scar recovery on hill pastures indicate that some erosion events do not recover pre-erosion pasture production even after 20 years (Lambert et al. 1984, Douglas et al. 1986). If erosion scars are not recovered, secondary events may occur eroding the bedrock, particularly on unconsolidated sandstone (O'Byrne 1967). In the past 40 years extensive areas of pastureland, susceptible to erosion, have been reforested with *Pinus radiata* (NZMF 1996). On land valuable for grazing, widely spaced-planted poplars or willows have been used to increase soil stability (Hicks 1995), while retaining the pastoral land use.

New Zealand work on the effect of tree planting on soil properties under widely spaced trees has been restricted largely to *P. radiata* agroforestry systems on flatland (Hawke & O'Connor 1993, Perrott et al. 1995, Hawke & Knowles 1997). To date, the effect on soil properties of exotic broadleaved, deciduous trees such as poplars has not been studied under New Zealand conditions. Overseas, authors (Singh et al. 1989, Jaswal et al. 1993, Kaul et al. 1983, Park et al. 1994, Thevathasan & Gordon 1997) have reported that poplar trees increase soil organic matter, nutrient status, and earthworm populations on cultivated land. Under poplar forest and plantation stands increases in soil pH, mineral nutrients and organic matter have been reported (Baker & Blackmon 1977, Bowersox & Ward 1977, Lousier & Parkinson 1979). Most changes have been attributed to mineral leaching from the canopy (Mahendrappa 1983) and leaf litter accumulation and decomposition (van Cleve & Noonan 1975). Care must be taken in extrapolating findings to widely spaced poplars as most of the published work was conducted in densely planted forestry or agroforestry systems.

The hypothesis formulated was that hill soils space planted with poplars had similar or better chemical, biological or physical soil properties when compared to adjacent stable open pasture. If space planted poplars have a similar effect to that reported in the literature for poplar systems then they might have a medium-term remedial role in the restoration of erosion scars, in addition to slope stabilisation of hill soil. Sites with mature trees, among the oldest in the region, were selected to obtain the clearest of the differences between the poplar planted and the unplanted areas.

4.3 Material and Methods

An exploratory glasshouse pot experiment examined the effect of soil media from a mature poplar-pasture and open pasture areas on soil pH, exchangeable cations, the germination and growth of commonly used forage species in New Zealand. This experiment is termed '*glasshouse experiment*'. A more comprehensive evaluation of the influence of mature poplar space planted poplar on soil properties was undertaken in a series of field studies reported here as the '*field survey*'.

4.3.1 Glasshouse experiments

4.3.1.1 Effect of soil media on pasture growth

Soil samples (0-20 mm depth) were taken from open pasture (OP) and poplar-pasture (PP) from Pohangina Hill 1 (see *Field survey* for details) areas in late December 1995. Soils were air-dried for one month inside a glasshouse and sieved (<3 mm). One kg of air-dried soil media was mixed thoroughly and packed in plastic pots and allowed to incubate for two months. The experiment was established in May 1996, at the Plant Growth Unit, Massey University, Palmerston North. Treatments were arranged as a 3 x 5 factorial with 3 replicates. One factor level was soil type: 1) open pasture topsoil (OPT), 2) tree-pasture top soil (PPT), and 3) 95% as treatment 1 plus 5% of dried, senesced poplar (*Populus deltoides*) leaves from the same site (OPT+L). The senesced leaves contained 1.23% N, 0.13% P, 1.21% K, 0.19% S, 1.9% Ca and 0.36% Mg. Five percent of senesced leaves corresponded to a leaf fall accumulation of 9 t ha^{-1} in a 20 mm soil stratum with a bulk density of 0.9 m^3 m^{-3}. The other factor level was pasture species: 1) Perennial ryegrass *(Lolium perenne)* cv. 'Grasslands Nui', 2) Cocksfoot (*Dactylis glomerata*) cv 'Grasslands Wana', 3) Lotus (*Lotus pedunculatus*) cv. 'Grasslands Maku' lotus, 4) White clover (*Trifolium repens*) cv. 'Grasslands Tahora' and 5) A mixture of all four. The pots were 160 mm high and 140 mm in diameter and had collecting saucers at the bottom. Pots were watered regularly and allowed to incubate for 2 months and any germinated seedlings were eliminated. Twenty viable seeds were then planted, and thinned to 4 plants per pot one month later. Nutrients were not added and legumes were not inoculated. Day/night temperatures in the glasshouse were 24/17°C. The trial was maintained with daily watering and regular harvesting of herbage at 50 mm height at approximately 2-weekly intervals for 11 months. The soil was then extracted from the roots by sieving and washing. Total shoot and root mass was measured and soil samples were obtained for pH analysis with the replicates being bulked. Soil samples collected at the beginning (after incubation) and end of the trial were bulked for the species treatment and analysed for pH, total N, S and P, organic C and S, plant available P and S, and exchangeable K, Ca, Mg and Na and anion storage capacity.

4.3.1.2 Effect of soil media on pasture germination

A parallel pot experiment was used to assess the effect of the soil treatments on seed germination, omitting the mixed species treatment. Twenty-five seeds of each herbage species were placed into pots of the same size and media content as described above. When the shoot reached 5 mm it was considered that the seed had germinated. Counts were made daily. When no increment in the number of germinated seeds was detected for 3 consecutive measurements, it was considered that maximum germination for that pot had been obtained. The temperature in the glasshouse averaged 24/17°C day and night during the experiment which was conducted under natural light during May and June 1996. Total shoot and root mass was recorded at the end of the experiment.

4.3.2 Field survey

4.3.2.1 Characteristics of sites with mature poplars

Soil samples were collected for analysis from three unreplicated sites with mature poplars and from a replicated experimental site with young trees. Mature *P. deltoides* clone I78 in widely spaced poplar-pasture stands (PP) were chosen, with adjacent open pasture (OP) on the same hillslope. Two of the sites, Hill 1 at 37 stems per ha (sph) and Hill 2 at 40 sph were located on a commercial livestock farm in the Pohangina Valley, longitude 175°53'E, latitude 40°08'S, 250 m above sea level (asl). The other site at 40 sph was a commercial sheep farm in the Rongoiti area (Rongoiti (longitude 175°44'E, latitude 37°30'S, 500 m asl). The trees were at least 29 (Pohangina) and 40 years old (Rongoiti) according to farm, photographic records or increment cores (see section 3.3.2.2 for Pohangina Hill 1). Average rainfalls at Pohangina and Rongoiti sites were 1200-1300 mm and 1150-1500 mm, respectively (Rijkse 1977, Campbell 1978). Both sites had experienced slip erosion and trees were planted to stop the process. Under the trees, soils on the debris tail, rather than on the headwall were sampled whereas open pasture soils showed no evidence of recent erosion (later than the tree planting), according to aerial photograph records, and formed an apparently stable headwall (Pohangina Hill 1 and Rongoiti). Hill 2 at Pohangina showed an earthflow form as opposed to the slip of Hill 1. Table 4.1 shows a profile description of the Pohangina Hill 1 soils at representative sampling points.

The hills of the Pohangina have a north-westerly aspect with a 20-25° slope, whereas the Rongoiti hill have a northerly aspect and a 18-25° slope on the debris tail. The soil of the Pohangina hill is an Oroua and Whetukura hill soils (Rijkse 1977) formed from soft sandstone which corresponds to a Dystrochept (USDA); the soil of the Rongoiti hill is a Mangamahu steepland association formed from consolidated silty sandstone (Campbell 1978). The hills of the Pohangina had received annual topdressings of 200 kg single super phosphate ha^{-1} during 1993 to 1995, 150 kg diamonium phosphate-13S ha^{-1} on August 1996 and 130 kg TSP-15S ha^{-1} on March 1997, whereas the Rongoiti hill had received no fertiliser in the last ten years. Low fertility grass species dominated all three pasture communities (see section 5.4.1.12). For these research sites, trees had formed a closed canopy (touching branches, see section 5.4.1.1) with grazeable pasture underneath.

Table 4.1. General description of soil profiles from open pasture and poplar-pasture areas at the Pohangina Hill 1 site.

	Open Pasture[1]				Poplar-Pasture			
Position	Mid slope				Hummocky mid slope on slip			
Aspect	295°				290°			
Slope	28°				18°			
	Horizons (cm)		texture	structure	Horizons (cm)		texture	structure
	0-16	Ah	fine sandy loam; 15% sub rounded greywacke stones up to 5 cm	moderate fine nut and medium crumb	0-3	Ah1	sandy loam	moderate coarse crumb and fine granule
					3-12	Ah2	fine sandy loam	weak fine nut and moderate medium crumb
	16-28	ABj	fine sandy loam; 40% sub angular weakly weathered greywacke stones mostly 1-2 cm but up to 20 cm	weak medium block breaking to moderate coarse crumb	12-14	Bj	fine sandy loam	medium weak crumb
	28-54	Bwj	sandy loam; 50% greywacke stones as above	moderate medium blocky and medium crumb				
	54-75	C	sandy loam; very stony as above	structureless	14-37	C	fine sandy loam, siltstone up to 3 cm	Structureless
					37-100	R	fine sandy loam, siltstone brittle	Structureless

[1] The open pasture profile corresponds to profile 7 in Appendix IV and the poplar-pasture profile corresponds to profile 4 in Appendix IV.

4.3.2.2 Sampling design in sites with mature poplars

Paired soil samples from 5 separate positions were obtained in June 1997 for Hill 1 at Pohangina and in October 1997 for Hill 2 at Pohangina and at Rongoiti. Each pair consisted of an OP and a PP area soil sample. Each of the 5 positions was randomly chosen and was related to a poplar tree at the PP area. Samples were collected at four sub-positions, half the distance from the crown edge and the tree trunk. The sub-positions were around the tree at 90° increments starting at the downhill aspect of the tree. For each sub-position, fifteen, 75 mm depth soil cores were obtained using a 25 mm-diameter corer and then bulked for chemical analysis, except for organic C and total N. Samples were analysed for pH, total N, P and S, organic C and S, plant available P and S, exchangeable K, Ca Mg and Na and anion storage capacity. For each sub-position, one 152 mm-diameter x 152 mm depth soil core was taken to measure invertebrate populations at Hill 1 at Pohangina, whereas at Hill 2 at Pohangina and at Rongoiti, two cores were taken per sampling position.

Hill 1 at Pohangina was the subject of more detailed study and additional determinations were made. Soil cores were obtained for the 75-150 and 150-300 mm soil strata for pH, available P, and S, exchangeable K, Ca Mg and Na, organic S and anion storage capacity analysis. Topsoil was sampled for bulk density (BD) at 0-75 and 75-150 mm depth using 115 mm-diameter cores gently hammered vertically into the soil. Using 150 mm-diameter cores, soil was sampled at the 0-75 and 75-150 mm soil depths to assess hydraulic conductivity and then for macroporosity and at 0-75 mm to determine soil texture. Invertebrate population was sampled again in October 1997, with two cores per sampling position.

4.3.2.3 Characteristics of the site with young poplars

Soil biophysical and chemical properties were also assessed in October 1997 on a site at Ballantrae AgResearch Hill Country Research Station (longitude 175°50'E, latitude 40°18'S) located 20 km from Palmerston North, New Zealand. Poplars were planted on the site in 1992 on a northeasterly aspect with an average slope (20-25°) and 300 asl. The hill had a number of large old slips delineated by full-length headwalls and the entire surface was covered with growing pasture. The soil is a Manganahu steepland soil (Stevens et al. 1993). The average annual rainfall is 1200 mm. The experimental areas have received annual topdressings of 150 kg RPR/E/S ha^{-1} since 1991 with little or no fertiliser prior to that date.

4.3.2.4 Sampling design in the site with young poplars

The experiment was arranged in a randomised block design with two treatments (OP and PP) and two replicates and 5 blocks. OP was dominated by low fertility grass species (Lambert et al. 1996), whereas the PP areas contained, in addition, widely spaced, planted *Populus spp.* at 50 to 100 sph. Each replicate was sampled at five points down the hill. For each replicate and block, samples were collected as described above, but the sub-positions bulked. Replicates in the PP were sampled in an area below the canopy of poplars at the five sampling points. Soil samples were analysed for pH, total N, S and P, organic C and S, available P and S and exchangeable K, Ca, Mg and Na and anion storage capacity (n=20). Two soil cores were taken to measure invertebrate populations (n=40).

4.3.2.5 Fertiliser distribution

On August 1996 at Pohangina Hill 1 the distribution of the aerial application of 150 kg diammonium phosphate (DAP)-13S ha^{-1} was measured with 240 plastic containers (300 mm diameter) at 12 positions in each environment in a cruciform arrangement at 2 m spacing between containers. The containers were positioned a few minutes before the application and collected 30 minutes after the application.

4.3.3 Analytical techniques

Soil pH was determined following Lee et al. (1991) determined on a 1:2.1 v/v water slurry left to stand for 16 hours at 20°C. Available P (Olsen P) was determined on a 1:20 v/v extract using 0.5 M sodium bicarbonate (pH 8.5 ±0.02 at 25°C), a modification of the method of Watanabe and Olsen (Blackmore 1987). Exchangeable K, Ca and Na were measured by flame emission spectrophotometry, while Mg was analysed by atomic absorption (Davies 1952) in a $K_2H_2PO_4$ extract. Total S and SO_4^{2-}-S were analysed according to Watkinson & Kear (1994). Organic S was obtained as the difference of total S and SO_4^{2-}-S. Anion storage capacity was determined by the method of Saunders (1965). Total N was determined colorimetrically after Kjeldahl digestion (Bradstreet 1965). Organic carbon was determined using a modification of the Walkley & Black (1943) method. A finely ground soil was wet oxidised with chromium trioxide, followed by colorimetric determination of the amount of reduced chromium present.

For BD soil samples were oven dried at 105 °C, and weighed. BD was calculated as the oven dry mass of soil divided by the volume of the sample container. Water stability of soil aggregates was measured by wet sieving soil crumbs with agitation under water (Williams et al. 1966). Hydraulic conductivity (K) was measured on intact soil cores, following saturation during three days in the laboratory, following the procedures of Ward & Hayes (1991) at four soil water pressure heads (ψ, –5, –20, –40, and –100 mm). BD was also determined on these samples. Intact cores collected for earthworm population assessment were handsorted for each of the main earthworm species. Numbers and mass by species were converted to units /m^2 (Springett 1985).

4.1.4 Statistical Analyses

4.3.4.1 Glasshouse

The statistical significance of the soil media and herbage species treatments of the glasshouse experiment were determined by analysis of variance using the GLM procedure (SAS Institute 1997). The significance level was set at $\alpha=0.05$.

4.3.4.2 Field survey

Statistical differences between OP and PP areas soil samples within site were detected with paired t-test (Steel & Torrie 1980). Differences in organic C and total N between the sample position around the tree and the open pasture were determined by ANOVA and one degree of freedom orthogonal contrast using the GLM procedure (SAS Institute 1997).

For the Pohangina and Rongoiti sites, the significant differences identified cannot be directly attributed to area management, as the samples were not from randomised replicates, and no information before tree planting was available. With the exception of the Ballantrae site, historical aerial photographs and the variation in soil properties including topsoil depth; depth to parent material suggested that the PP had suffered greater disturbance compared with the OP areas. Many of the properties of soil at the time of planting for the PP area may therefore reflect the loss of topsoil and been more characteristic of properties of a lower, less developed profiles. If poplars have a beneficial effect in restoring soil fertility than the open pasture then the soil properties should be similar or better in the long term under the trees.

For the Ballantrae experiment, ANOVA was used (SAS Institute 1997) to determine the statistical significance of the effects. The significance level was set at $\alpha=0.05$ for all tests.

Changes in hydraulic conductivity ($K(\psi)$) with tension (K_5, K_{20}, K_{40}, K_{100}) were modelled using a non-linear regression (Jandel 1995) of the form $K(\psi)_i=\beta_0 + \beta_1 e^{-\beta_2 \psi}$ where β_0 was the intercept, β_1 in an asymptotic value for $K(\psi)$ as $\psi \rightarrow \infty$, β_2 is the rate at which a logarithmic function $K(\psi)$ changes linearly per unit of ψ, and i is the soil sample core. Differences between vegetation areas for the parameters of the $K(\psi)$ curve were tested by least squares analysis of variance (García-Muñiz et al. 1998) using the GLM procedure (SAS Institute, 1997).

4.4 Results

4.4.1 Glasshouse experiment

Soil pH was highest for the OPT+L treatment ($P<0.05$), while the other two treatments were not significantly different ($P>0.05$) at the end of the study (Table 4.2). At the beginning of the experiment, all soil media treatments were different ($P<0.05$). The addition of 5% of senesced poplar leaves increased organic and plant available S (SO$_4^{2-}$-S), exchangeable K, Mg and pH by 1.2 units over the OPT treatment after two months of incubation (Table 4.3). Lotus growth resulted in the lowest ($P<0.05$) soil pH, while the grass species produced the highest pH at the end of the experiment (Table 4.2). There was a tendency for the pH to increase over time in all soil media treatments. Table 4.3 presents the levels of plant available minerals at the beginning and end of the experiment. Considering these values, it appeared that the 40 mg/kg of K could constrain growth in the PPT and OPT treatments while the 18 mg/kg of P did the same for the OPT and OPT+L treatments. Calcium and Na apparently increased in the PPT and OPT+L treatments but not in the OPT, probably as a consequence of litter mineralisation. Organic and SO$_4^{2-}$-S were the only means that increased in the OPT after the growth period.

Table 4.2. Effect of soil media and pasture species treatments on soil pH and dry matter accumulation on a pot experiment over 11 months. Initial pH means were obtained after the incubation period.

Soil media[1]	Soil pH initial	Soil pH final	Accumulated dry matter (g)
Poplar-pasture topsoil	5.4b	5.8a[2,3]	32.1c
Open pasture topsoil	4.9a	5.6a[3]	15.8a
Open pasture topsoil + %5 senesced leaves	6.1c	6.9c	23.3b
SEM[4]		0.04	0.45
Forage species			
Ryegrass		6.3c	13.4a
Cocksfoot		6.3c	14.8a
Lotus		5.8a	33.2c
White clover		6.0b	29.4b
Mixture		6.0b	28.1b
SEM		0.06	0.58

[1] Treatments were: PPT, poplar-pasture topsoil, OPT, open pasture topsoil and OPT+L, open pasture topsoil with 5% senesced poplar leaves.

[2] Within a main effect, within a column, figures with same letter, were not significantly different ($P>0.05$).

[3] Figures were different at ($P<0.07$).

Total dry matter (TDM) accumulation was different for all soil media treatments, with the PPT having the highest yield, and OPT the lowest (Table 4.2). The differences were evident throughout the experiment and kept the same order at each harvest. The lotus treatment had the

Table 4.3. Soil minerals at the start and end of the experiment for the soil media effect.

	Organic		Plant available				Exchangeable							
	S		P (Olsen)		SO$_4^{2-}$-S		Ca		K		Mg		Na	
Treatment	initial	final	initial	final	initial	final	initial	final	initial	final	initial	final	initial	final
main effect							(mg/kg)							
PPT	18	30	45	33	38	30	1125	1375	340	40	300	265	85	130
OPT	7	18	23	18	11	19	750	750	120	40	135	90	65	95
OPT+L	11	20	20	18	59	16	875	1250	480	100	205	160	95	145

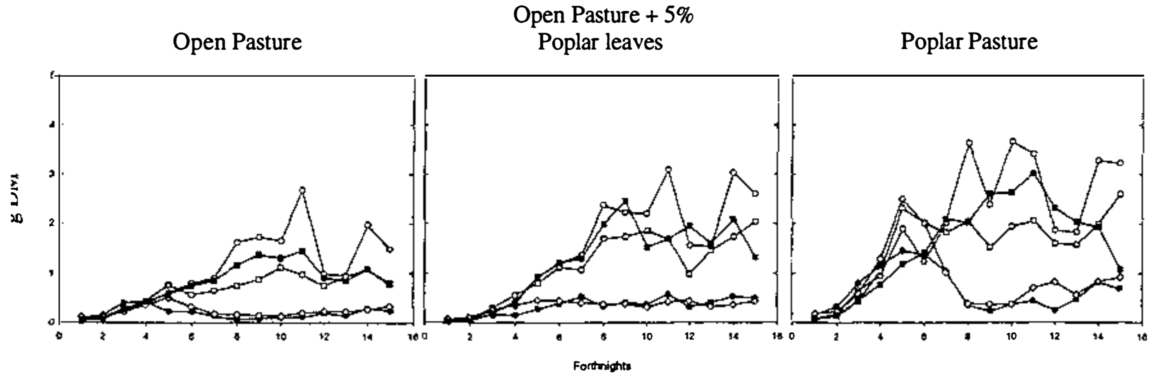

Figure 4.1. Plant DM yield for soil media treatments in a glasshouse pot experiment. Symbols represent the yield of cocksfoot (•), lotus (○), mixed species (☐), ryegrass (∇) and white clover (■).

highest TDM ($P<0.05$). White clover and the mixture treatments were not significantly different ($P>0.05$) but both were lower than the lotus treatment ($P<0.05$). Cocksfoot and ryegrass were the lowest yielding from all treatments ($P<0.05$). The consistency of the media treatments was confirmed by the absence of significant interaction with the herbage species ($P>0.05$). Initially, ryegrass was the fastest growing species, particularly in the PPT treatment, but after a few months it declined and the lotus and white clover had more persistent growth rates (Figure 4.1).

Table 4.4. Effects of soil media and herbage species on germination and initial plant growth.

Soil media[2]	Germination[1]	Plant growth shoot	Plant growth root
	(%)	(g/plant)	
PPT	37a[3]	0.0040a	0.0040a
OPT	48b	0.0036a	0.0046a
OPT+L	57c	0.0053b	0.0067a
SEM[4]	2.9	0.0003	0.0008
Ryegrass	36a	0.0079d	0.0025a
Cocksfoot	38ab	0.0047c	0.0035a
Lotus	46b	0.0014a	0.0100b
White clover	69c	0.0032b	0.0042a
SEM	3.4	0.0004	0.0009

[1] Maximum germination 10 days after sowing.

[2] Treatments were: PPT, poplar-pasture topsoil, OPT, open pasture topsoil and OPT+L, open pasture topsoil with 5% senesced poplar leaves.

[3] Within a main effect, within a column, figures with same letter, were not significantly different ($P>0.05$).

[4] Pooled standard error of the mean.

Pasture seed germination after 10 days of sowing differed between treatments, with OPT+L having the highest germination count (Table 4.4). White clover germination count was greater than the other species ($P<0.05$). Differences in germination counts between species were attributed to their different germination potential since the interaction between soil media and pasture species was not significant ($P>0.05$). Shoot growth of OPT+L was different from the other treatments ($P<0.05$), but plant root growth was not significantly different amongst the soil media treatments. Shoot growth was different for all species treatments, with grasses having higher growth than the legumes ($P<0.05$). Only lotus had a significantly different root accumulation for the species main effect ($P<0.05$). The root accumulation results showed higher standard errors that were attributed to the root recovery errors of small seedlings.

4.4.2 Field survey

4.4.2.1 Soil pH and exchangeable bases

Soil pH was significantly higher ($P<0.05$) in the PP at all sites by at least 0.5 units (Table 4.5). Exchangeable bases were also higher in the PP of the sites with mature poplars (Table 4.5), but only significantly different at the $P<0.10$ level for Ca and Mg at the site with younger trees (Ballantrae). The finding of a higher pH under the poplar trees was confirmed by the significant difference ($P<0.01$) in pH of a similar magnitude from paired soil samples (0-75 mm depth) from 6 additional sites in the Manawatu-Whanganui and Rangitikei districts with widely spaced poplars ranging in age from 15-30 years approximately. These samples were analysed for pH only. Anion storage capacity (ASC) was significantly ($P<0.05$) different for all the measured sites. For the sites with mature poplars ASC was lower ($P<0.05$) in PP than in OP.

Table 4.5. Soil pH, exchangeable bases and anion storage capacity (ASC) at the 0-75 mm soil stratum in open pasture (OP) and poplar-pasture (PP) vegetation areas.

Site	Area	pH	Ca	K	Mg	Na	ASC
					kg/ ha^{-1}		
Pohangina	OP	5.5a	446.4a[1]	68.2a	85.5a	3.5a	21.8a
hill1	PP	6.0b	657.0b	154.0b	146.6b	4.5b	14.4b
	SEM[2]	0.0	27.9	13.0	7.2	0.01	0.6
Pohangina	OP	5.4a	477.3a	48.9a	72.1a	20.4a	25.1a
hill2	PP	6.6b	716.0b	233.9b	133.3b	21.7a	15.4b
	SEM	0.1	28.6	14.6	4.4	1.4	1.2
Rongoiti	OP	5.7a	882.1a	118.5a	134.3a	na[3]	na
	PP	6.5b	1879.6b	221.9b	157.9b	na	na
	SEM	0.0	95.6	13.7	5.2		
Ballantrae	OP	5.4a	434.7a[4]	97.9a	82.9a[4]	21.7a	29.2a
	PP	5.9b	519.9a[4]	102.0a	110.5a[4]	32.9a	25.7b
	SEM	0.1	22.5	10.5	4.6	1.9	1.3
Other six	OP	5.4a	na	na	na	na	na
lower North	PP	6.1b	na	na	na	na	na
Island sites	SEM	0.1					

[1] Within site, within column, figures with same letter were not significantly different ($P>0.05$).
[2] Pooled standard error of the mean.
[3] Not analysed.
[4] Within site, within column, figures were significantly different ($P<0.10$).

4.4.2.2 Soil mineral pools

Organic C and total N were not different ($P>0.05$) between the OP and PP when expressed as a percentage. However, the organic C and total N soil pool sizes (t/ha) were different ($P<0.05$, organic C in Pohangina Hill 1 only at $P<0.1$) for the OP and PP in the Pohangina sites where the PP pools had a smaller size (Table 4.6). There was an indication that total N in the PP was also lower at the younger tree Ballantrae site. The size of the soil total N pool increased progressively with total C concentration in both the OP and PP in the Pohangina sites (Figure 4.2). However, there was considerable scatter and different trends in the OP and PP in the Ballantrae site (Figure 4.2). With the exception of the West aspect from the tree trunk, total N pool size at all positions around the tree trunk were different ($P<0.05$) from the OP in the Pohangina Hill 1 site (Table 4.7). The organic C soil pool size was different only between the south aspect of the tree and the OP.

Total P and S were only different at Pohangina Hill 2 with the PP having lower values. Plant available P and S (Table 4.8) revealed that all sites were of low fertility. Olsen P was significantly different at the Pohangina Hill 1 areas, but not at the other sites. SO_4^{2-}-S was not significantly different between the vegetation areas at any site. No differences were evident at the younger tree Ballantrae site. The ratios for C:N:P:S were comparable for the OP and PP at all sites (Table 4.8).

Table 4.6. Bulk density and mineral pools at the 0-75 mm soil stratum in the open pasture (OP) and poplar-pasture (PP) vegetation areas.

		Pohangina Hill 1[1]			Pohangina Hill 2			Rongoiti			Ballantrae		
	units	OP	PP	SEM[2]	OP	PP	SEM	OP	PP	SEM	OP	PP	SEM
Bulk Density	Mg/m^3	1.11a[3]	1.07a	0.02	0.96a	0.95a	0.02	0.80a	0.79a	0.01	0.92a	0.91a	0.01
Organic C	t/ha	34.5a[4]	31.7a[4]	1.2	29.9a	19.0b	2.6	na[5]	na		24.4a	25.5a	1.8
Total N	t/ha	3.0a	2.7b	1.0	2.4a	1.9b	0.1	na	na		2.4a	2.1a	0.1
C:N ratio[6]		8.9:1a	9.6:1a	0.3	12.3:1a	9.8:1b	0.5	na	na		10.1:1a	12.3:1a	0.8
Phosphorus													
available	kg/ha	12.2a	7.1b	0.7	5.7a	4.6a	1.3	9.4a	7.6a	0.9	7.3a	7.8a	0.6
total	kg/ha	564a	548a	29	461a	305b	29	na	na		571a	612a	31
Sulphur													
sulphate	kg/ha	3.9a	4.2a	0.3	3.8a	4.5a	0.7	3.7a	7.7a	1.7	4.3a	12.9a	2.3
organic	kg/ha	5.4a	6.1a	0.4	1.9a	1.6a	0.3	na	na		2.3a	3.5a	0.4
total	kg/ha	na	na		345a	219b	17	na	na		469a	412a	21

[1] Pohangina Hill 1 was sampled on June, the other sites on October 1997.
[2] Pooled standard error of the mean
[3] Within site, within column, figures with same letter were not significantly different ($P>0.05$).
[4] Figures were different at $P<0.1$.
[5] Not analysed.
[6] Calculated for individual soil samples.

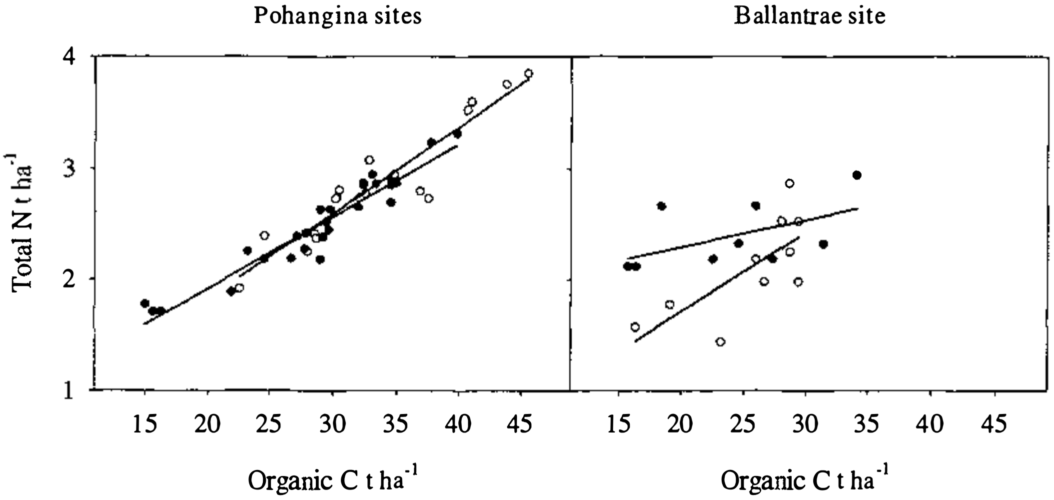

Figure 4.2. Relationship between soil organic C and total N sampled at 0-75mm soil depth in the open pasture (OP, o) and poplar-pasture (PP, •) vegetation areas from Pohangina sites and Ballantrae site.

Table 4.7. Organic C and total N soil proportions and pool sizes area sampled at 0-75mm soil stratum in open pasture (OP) and around trees in the poplar pasture (PP) in the Pohangina Hill 1 site.

		Total N		Organic C	
PP		%	t ha^{-1}	%	t ha^{-1}
	North	0.31a[1]	2.46a	3.9a	29.84ab
	East	0.32a	2.55a	3.9a	30.48ab
	South	0.33a	2.56a	3.9a	29.78a
	West	0.34a	2.86ab	4.0a	33.53ab
OP		0.36a	3.01b	4.1a	34.53b
	SEM[2]	0.02	0.16	0.23	1.99

[1] Within column, figures with same letter were not significantly different (P>0.05).

[2] Pooled standard error of the mean

Table 4.8. Ratios for organic C and total N, P and S area sampled at the 0-75mm soil stratum in the open pasture (OP) and poplar-pasture (PP) vegetation areas. Ratios were calculated from means of each element.

	Open pasture				Poplar-Pasture			
	C	N	P	S	C	N	P	S
Pohangina								
Hill 1	100	15	1.7	na[1]	100	13.9	1.6	na
Hill 2	100	8	1.5	1.2	100	10	1.6	1.2
Ballantrae	100	9.8	2.3	1.9	100	8.2	2.4	1.6

[1] Not analysed.

4.4.2.3 Fertility changes in the soil profile

Soil pH and exchangeable bases were higher ($P<0.05$) in all soil strata in PP than in OP at Pohangina Hill 1 (Table 4.9). The highest concentration of exchangeable bases was found at the shallower soil stratum (0-75mm) with Ca, K and Mg being 41%, 116%, 64% higher, respectively, in the PP. Soil P was lower in the 0-75 and 75-150 mm soil strata, while there was no difference in SO_4^{2-}-S or organic S ($P>0.05$). Levels of SO_4^{2-}-S and organic S were not significantly different at any strata.

Soil fertility within the OP and PP decreased with increasing soil depth for all measured nutrients ($P<0.05$). This trend was consistent since the interaction between vegetation area and soil depth was not significant ($P>0.05$). Except for Ca and K in the OP area and Na in the PP, available nutrients were different between the 0-75 mm and the 75-150mm soil strata ($P<0.05$). With the exception of P at the OP, nutrient levels were not different between the 75-150 mm and 150-

300 mm soil strata (P>0.05). Nutrient concentration was always different between the 0-75 mm and the 150-300 mm soil strata (P<0.05). Plant available P, K and S concentrations at the 75-150 and 150-300 mm soil strata were approximately half or lower than the measured concentration at the 0-75 mm soil stratum (P<0.05).

Table 4.9. Soil pH, exchangeable bases, sulphur and phosphorus for different soil strata of open pasture (OP) and poplar-pasture (PP) areas at Pohangina hill 1 on June 1997.

	pH			Calcium (mg/ kg)			Magnesium (mg/ kg)		
Soil strata	OP	PP	SEM[1]	OP	PP	SEM	OP	PP	SEM
0-75 mm	5.53a[2]	6.01b	0.04	796.9a	1125.0b	37.0	153.1a	251.3b	10.4
75-150 mm	5.59a	5.93b	0.04	703.1a	859.4b	37.0	118.8a	206.9b	10.4
150-300 mm	5.61a	5.98b	0.04	640.6a	796.9b	37.0	116.3a	210.6b	10.4
All strata	5.57a	5.97b	0.02	713.5a	927.1b	21.3	129.4a	222.9b	6.0

	Potassium (mg/ kg)			Phosphorous (mg/ kg)			Sodium (mg/ kg)		
Soil strata	OP	PP	SEM	OP	PP	SEM	OP	PP	SEM
0-75 mm	122.5a	265.0b	19.0	20.9a	12.7b	0.9	31.9a	38.8b	1.7
75-150 mm	70.0a	160.0b	19.0	8.9a	5.5b	0.9	23.1a	34.4b	1.7
150-300 mm	60.0a	142.5b	19.0	6.1a	4.7a	0.9	23.1a	33.1b	1.7
All strata	84.2a	189.2b	11.0	12.0a	7.6b	0.5	26.0a	35.4b	1.0

	Organic Sulphur (mg/ kg)			SO_4^{2-}-S (mg/ kg)		
Soil strata	OP	PP	SEM	OP	PP	SEM
0-75 mm	6.8a	7.4a	0.5	6.6a	7.5a	0.5
75-150 mm	3.0a	4.3a	0.5	3.6a	5.0a	0.5
150-300 mm	3.0a	3.1a	0.5	3.5a	4.0a	0.5
All strata	4.3a	4.9a	0.3	4.6a	5.5a	0.3

[1] Pooled standard error of the mean.

[2] Within row, within classification, means with same letter were not significantly different (P>0.05).

4.4.2.4 Soil physical properties

Soils from the OP and PP in Pohangina Hill 1 had similar soil texture, although the soil was younger at the PP area (Table 4.1). For the OP and PP areas sand (2.00-0.05 mm) was 61.5% and 60%, silt (0.05-0.002 mm) 24.5% and 28.0% and clay (<0.002 mm) 14.0% and 12.0%, respectively. BD was similar (P>0.05) for the OP and PP areas (Table 4.6) at all measured sites. In models fitted to the $K(\psi)$ data collected at K_{-5}, K_{-20}, K_{-40} and K_{-100} within a vegetation area and soil strata, the soil water pressure head (ψ) accounted for a high proportion of the variation ($R^2>0.97$) of $K(\psi)$ (Figure 4.3). $K(\psi)$ distribution was found to be similar (P>0.05) for the vegetation areas and soil strata, according to the analysis of the non-linear regression parameters. The similarity in pore function of soil, the soil from OP and PP was further supported by no significant differences (P>0.05) between vegetation areas in total porosity (Table 4.10) or water aggregate stability at Pohangina Hill 1 (Table 4.11).

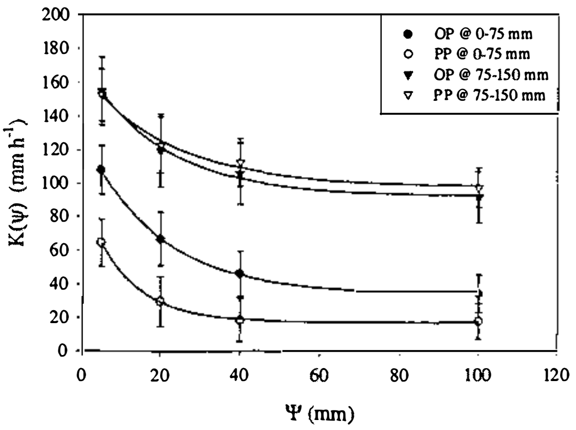

Figure 4.3. Hydraulic conductivity K(ψ) for soil samples from the Pohangina Hill 1 open pasture (OP) and poplar-pasture (PP) vegetation areas at two soil strata. The lines represent a non-linear model of K(ψ) as function of various ψ. Soil conductivity models of OP and PP soils were not significantly different within soil depth (P>0.05).

Table 4.10. Total porosity (m^3 m^{-3}) for different soil strata of open pasture (OP) and poplar-pasture (PP) vegetation areas at Pohangina Hill 1 on June 1997.

Soil strata	OP	PP	SEM[1]
0-75 mm	59.8a[2]	58.5a	1.2
75-150 mm	47.4a	46.3a	1.1
0-150 mm	53.6a	52.4a	1.0

[1] Pooled standard error of the mean.

[2] Within row, within classification, figures with same letter were not significantly different (P>0.05).

Table 4.11. Water stable aggregates sampled at the 0-75 mm soil stratum in areas with open pasture (OP) or poplar-pasture (PP) vegetation at Pohangina Hill 1 on June 1997.

	Water stable aggregates %		
Size	OP	PP	SEM[1]
> 2 mm	66.7a[2]	64.6a	1.8
1-2 mm	13.4a	12.4a	1.8
1-0.5 mm	3.4a	4.3a	1.8
< 0.5 mm	83.6a	81.3a	1.8
All sizes	41.8a	40.6a	0.9

[1] Pooled standard error of the mean.

[2] Within row, within classification, figures with same letter were not significantly different (P>0.05).

4.4.2.5 Soil earthworm population

The OP earthworm mass/m^2 (0-150 mm soil depth) was lower ($P<0.05$) in spring than winter at Pohangina Hill 1 (Figure 4.4), earthworm numbers/m^2 were consistently lower in the PP at both sampling dates. Earthworms were 649 and 161 m^2 ±57.1 SEM for the OP and PP, respectively in July and 386 and 95.4 /m^2 ±48.7 SEM, for OP and PP in October. Earthworm mass was 272.8 and 60.6 g m^2 ±31.3 SEM for the OP and PP, respectively in July and 101 and 55 g m^2 ±25.1 SEM in October. The similar earthworm mass/m^2 between the OP and PP in the spring but not in the winter suggested that population dynamics, and not only mass and number, were different between the OP and PP. On the other hand, Pohangina Hill 2 showed the opposite earthworm populations. At this site, earthworm population tended to be higher for the PP ($P<0.07$), earthworm numbers were 413.4 and 651 /m^2 ± 89.8 SEM for the OP and PP respectively, and masses were 112.6 and 172.2 g m^2 ±22.6 SEM. Hill 2 had a more northerly aspect than Hill 1, so, soil temperature might have had an influence on earthworm population. Although it was measured at a time different from the sampling date, soil temperature at 100 mm depth indicated that Hill 1 was colder ($P<0.05$) than Hill 2 during November 1997 (15.0 vs. 16.1 °C). However, soil temperature was similar for both Hills ($P>0.05$) in December 1997 (18.5 vs. 18.6 °C) and January 1998 (18.0 vs. 18.4 °C).

At Rongoiti (Figure 4.4), earthworm numbers/m^2 were higher for OP, but worm mass/m^2 was similar for OP and PP. Earthworms were 1007 and 673 /m^2 ±89.4 SEM for the OP and PP, respectively and 252 and 270 g m^2 ±38.3 SEM, respectively. Mature earthworm forms were more numerous, although by mass/m^2, mature and immature classes had similar values. *A caliginosa* was the predominant species, followed by *A. longa* and *Lumbricus rubellus.* The similar earthworm mass m^2 for OP and PP at Rongoiti was explained by the significant ($P<0.05$) interaction between the vegetative cover and the worm species *A. longa*, with 48.4 and 29.1 g m^{-2} for OP and PP, respectively. Otherwise, earthworm mass m^2 for the different species was similar PP in comparison with the OP.

For Ballantrae (Figure 4.5), total earthworm number/m^2 and mass/m^2 were similar ($P>0.05$) between the OP and PP areas (657 and 596 /m^2 ±88.9 SEM and 129.2 and 117.8 g m^2 ±14.7 SEM, respectively). Immature earthworm classes were predominant. *Allolobophora caliginosa*, followed by *A. rosea* and *Lumbricus rubellus* were the dominant species. As this site had the youngest poplars, small or no differences would be expected given the low tree density and the low leaf and root biomass per tree.

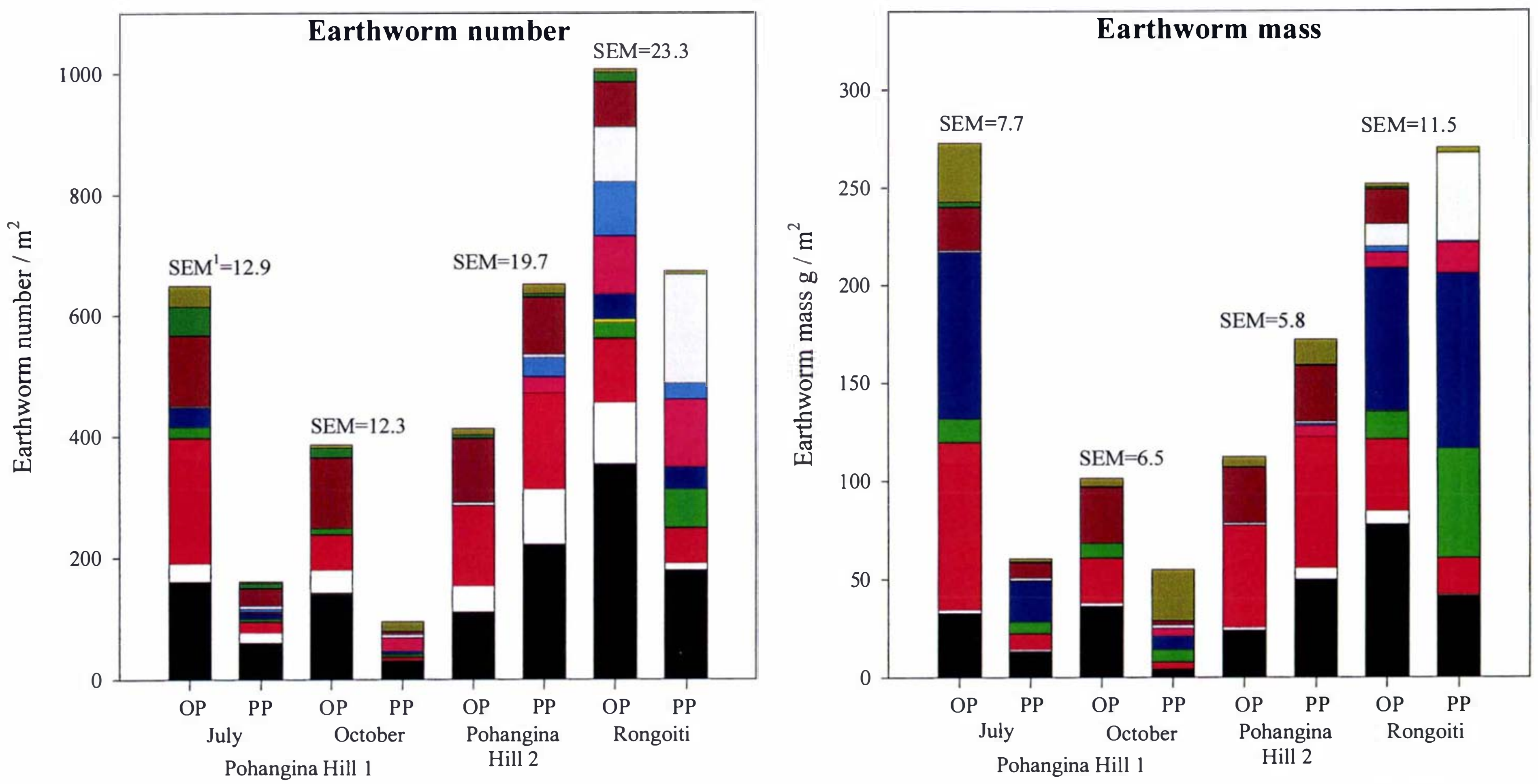

Figure 4.4. Means for earthworm populations in open pasture (OP) and poplar-pasture (PP) areas in sites with mature poplar trees. The Pohangina Hill 2 and Rongoiti sites were sampled in October 1997. In addition, Pohangina Hill 1 was sampled in July 1997. Classification of earthworm species and development phase is given by the inset table.

[1] pooled standard error of the mean

	Phase class		
Species	imature	juvenile	mature
A. caliginosa	■	□	🟥
A. longa	🟩	🟨	🟦
A. rosea	🟥	🟦	□
L rubellus	🟫	🟩	🟫

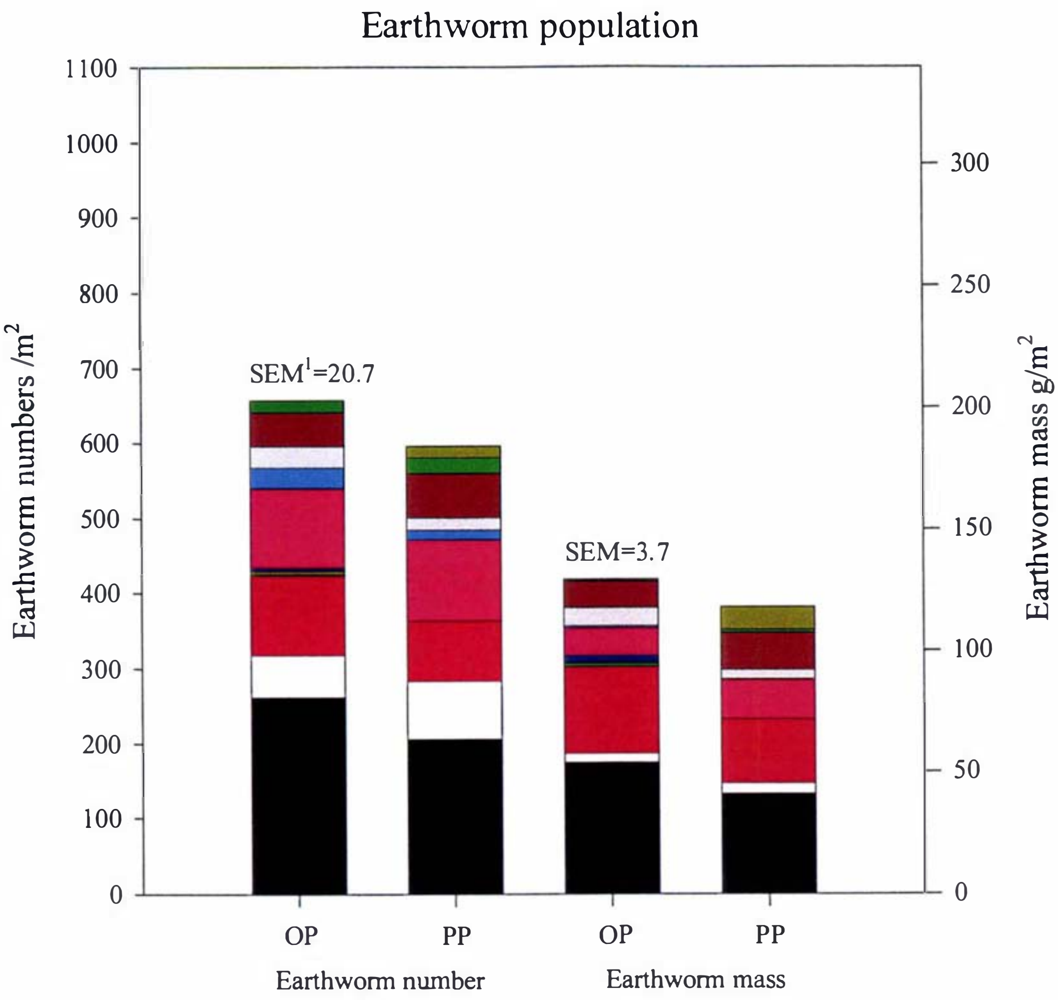

Figure 4.5. Means for earthworm populations in open pasture (OP) and poplar-pasture (PP) areas in the Ballantrae site in October 1997. The inset table in Figure 4.4 gives classification of earthworm species and develop-

4.4.2.6 Fertiliser distribution

There were no differences in fertiliser distribution between the vegetation areas. The amount of fertiliser collected was 81.2 ±8.15 for PP and 77.5 ±9.0 kg ha^{-1} for OP. Although the recovery of fertiliser was lower than the amount applied, the standard error of the mean for the OP and PP was similar, indicating that the trees did not increase the variation in the collecting procedure.

4.5 Discussion

4.5.1 Glasshouse experiment

The finding of positive, rather than negative interaction between forage legumes and poplar-pasture topsoil or open pasture topsoil plus poplar leaves treatments in germination and early growth in this study does not agree with the result of Tann (1986). His work showed a markedly lower nitrogenase activity in soils of montane aspen (*Populus spp.*), and an inhibitory effect on plant growth by water soluble or volatile extracts from poplar litter when applied to cultivated soils (Tann 1986). It was possible that these compounds were lost during the incubation period or were not present in the leaf-only material used in the open pasture topsoil plus poplar leaves treatment. Results from a field study at Pohangina Hill 1 (Guevara-Escobar et al. 1997) showed that pasture accumulation and botanical composition (i.e. legumes) were similar ($P>0.05$) during the winter months for the OP and PP vegetation areas (see section 5.4.1.12). This evidence suggested that any negative effect of poplar soil or leaf substances might be only transitory in nature.

The incorporation of 5% poplar leaf litter into open pasture soil resulted in superior germination (48 vs. 57.3% for the OPT and OPT+L, respectively) and early development of the test forage species (0.0036 vs. 0.0067 g/plant after 10 days, respectively). The better performance of the poplar-pasture topsoil treatment and particularly that of legumes was attributed to a higher soil pH at the beginning of the experiment than the other treatments. In contrast, the open pasture topsoil treatment had a lower nutrient status at the beginning and end of the experiment. Soil nutrient status for open pasture topsoil plus poplar leaves suggest that the senesced leaves were able to supply sufficient nutrients to support increased pasture accumulation when compared to the open pasture topsoil only treatment (see section 5.4.1.15).

The higher DM yield of legume-containing treatments was attributed to their ability to fix N. The mixed species treatment was superior to the grass treatments but lower yielding than the lotus treatment. Mixed species treatments usually are lower yielding than the highest yield monoculture tested in a controlled environment (Garnier et al. 1997). Ryegrass and cocksfoot initially had growth rates equal to or higher than the legumes but growth declined rapidly, indicating that N was the first nutrient to limit growth. The white clover treatment had, at some times, growth rates comparable to those of lotus, but declined earlier than the lotus containing treatments, indicating that P had become limiting particularly in the treatments containing soil from the open pasture. The incubation of soil media for 60 days before the start of the study allowed decomposition of the senesced material in the OPT+L treatment and the mineralisation of nutrients to some extent. At the end of the experiment, when soil media were extracted, some leaf debris particles (5mm diameter) were still visible indicating that decomposition was incomplete.

The study indicated that topsoil amended with leaf litter an also poplar-pasture topsoil enhanced germination rates and can support greater pasture accumulation than open pasture topsoil where light is adequate. In part, this potential is attributed to the mineralised nutrients from the leaf litter material. The effect of the treatments on germination of pasture species was difficult to explain. But it is possible that other compounds different from leaf litter leachate were involved. Although the prescribed 5% of senesced leaves in the open pasture topsoil plus poplar leaves treatment corresponded to the leaf litter accumulation that occurs in poplar plantations (Singh et al. 1989), it was three times the amount of litter fall measured during the autumn of 1998 at the Pohangina Hill 1 site (see section 5.4.1.11). The addition of leaf litter to the open pasture treatment considered only the most labile component of the tree debris. More fibrous material such as bark, branchwood and twigs would decrease the rate of decomposition. Animals eating leaf litter would increase the rate of decomposition of leaf material but change the distribution and flux of organic matter in to the soil and change nutrient availability. In the long term, the decomposition of tree material will lead to higher nutrient status as the effect of the poplar-pasture topsoil treatment demonstrated.

Comparison of the soil media used in the glasshouse with the samples obtained in the field survey from the Pohangina Hill 1 corroborated the findings of the pit profile description indicating greater fertility in the surface of the mineral soil. While the open pasture topsoil had a similar P and K concentration at the 0-20 (Table 4.3) and 0-75 mm (Table 4.9) soil strata, the poplar-pasture topsoil had 45 and 12.7 mg/kg of P at the same stratum, respectively. Potassium also was higher in the poplar-pasture topsoil at the 0-20 mm than the 0-75 mm soil stratum (340 vs. 265 mg/kg). Therefore, the soils were young because the deposited organic matter by the poplars and pasture was not uniformly distributed as in the open pasture. Nutrient distribution within the topsoil may be reflected in the shallower distributions of fine roots (presumably pasture roots) in the most superficial soil stratum in the poplar-pasture area (Appendix II).

4.5.2 Field survey

Soil chemical analysis revealed that at all the sites, both the OP and PP areas were of low fertility typical of much of New Zealand hill country, including those of the Pohangina County (Rijkse 1977). Exchangeable bases, with the exception of Mg, plant available P and S were from low to very low for New Zealand pasture conditions (Blackmore et al. 1987). A lower ASC in the PP areas was indicative of a less developed or weathered soil. In the PP an increase in pH is likely to decrease the positive charges and thereby decreases the anion retention capacity, and could explain the small difference in P between the OP and PP (Roberts *et al.* 1996). There are two possible explanations for this difference Firstly, soil under the poplars was younger in origin, as a consequence of past soil erosion. Secondly, slower weathering rates might result from the higher pH and lower leaching volumes (e.g. to rainfall interception) from the soil under the trees.

4.5.2.1 Soil pH and exchangeable bases

Mean soil pH of poplar-pasture areas was consistently 0.5 to 1.2 units higher than in the open pasture. Measurements at the additional six sites in the region also found similar differences in soil pH in the OP and PP, indicating that pH differences were unlikely to be the result of natural variation (McIntosh et al. 1997). The higher pH in the PP was attributed to a number of factors resulting from poplar-pasture interaction. From the incubation study it was shown that adding poplar leaf litter increases soil pH (Table 4.2). Tree canopy reduces effective rainfall (see section 3.4.2) and possibly changes rainfall pH, modifies or reduces seasonal patterns of sulphate and nitrate leaching. NO_3^-/NH_4^+ poplar N nutrition is another intervening factor. Also, shading reduces legume growth (see section 5.5.3.1) and potentially N-fixation. At this point, only the factors related to soil nutrient cycling are discussed in this Chapter. A general discussion follows in section 6.3.2.

By cycling nutrients via litter fall, soils from the PP received leaf litter inputs with a high cation content (Ca 1.9%, K 1.2%, Mg 0.36%). This suggests that exchangeable bases were accumulated over time. Water-saturated aspen leaf litter has been found to lose about 24% of total weight in one day (Taylor & Parkinson 1988b), and probably intracellular ions would be rapidly incorporated into the soil. Poplar leaf litter would be equivalent to 148 kg Ca ha^{-1} yr^{-1} applied as lime at Pohangina 1. Annual addition of this much of Ca through leaf litter is likely to cause a significant change in the pH of these low pH buffering soils. The potential effect of poplar leaf litter Ca^{++} was in a favourable direction, but was not of an order of magnitude sufficient to explain the effect on soil acidity (Young 1997). On the other hand, it has been suggested that poplars have a decreased ability to absorb Ca^{++} as compared with K^+ and this could explain the reduction in ionic competition in poorer soils (Liani 1972). Other bases (i.e. K^+ and Mg^{++}) and complexing of Al^{3+} by humus may also reduce the amount of free H^+ (Dodd et al. 1992). The higher Mg^{++} and Na^+ concentration in the PP vegetation area soils could also be partially attributed to sea salt deposition (Parfitt et al. 1997). These ions eventually may be washed away in throughfall and deposited in the soil (Potter et al. 1991).

In the absence of any information on the effect of crown sampling position on Ca^{++} concentration in foliage and litter samples, freshly senesced leaves were collected from beneath the trees and from the lower branches of the canopy. These were assumed to be representative of the whole canopy of poplars at the Pohangina Hill 1 site. In eucalyptus, although having a much lower Ca^{++} concentration in the leaves than poplars, variation in Ca^{++} leaf content was observed in accordance to upper, mid or lower crown position (Lamb 1976). Attiwill (1980) not only reported that Ca^{++} distribution was uneven in eucalyptus, but also was irregularly distributed in other biomass components such as bark or branchwood, particularly in older trees. Thus, an additional source of Ca^{++} available to the soil pool could come from poplar bark and branch decomposition and not only from leaf litter.

After the application of lime, soil reacidifies at rates ranging from 0.02 to 0.075,pH units year^{-1} (Wheeler 1997). Ca^{++} and Mg^{++} concentration in soil from poplars, alone or mixed, has been found to increase over time (Bowersox & Ward 1977, Joshi et al. 1997) and to be higher when compared with soils from under indigenous (Joshi et al. 1997) or coniferous forest (van Cleve & Noonan 1975, Troth et al. 1976). It is possible that grazed PP associations would not have the same cation balance as in poplar forests because pasture nutrient uptake and N fixation still must have an effect on the reacidification rate.

Soil alkalisation by poplar contrasts with radiata pine soil acidification when both are compared with pasture soils (Perrot et al. 1995, Parfitt et al. 1997, Yeates et al. 1997). This is attributed to cation uptake by pines and release of organic acids (Giddens et al. 1997). In particular, NH_4^+ nutrition always leads to excretion of H^+ ions by roots (Gisman 1994). N nutrition in poplars is based on NO_3^-, in fact, poplars are sensitive to NH_4^+ (Peuke & Tischner 1994). Also, organic matter mineralisation was found to be slower under pines when compared with poplars because pine needles have slow decomposition rates (Taylor & Parkinson 1988a). In addition, *P. radiata* has little Ca^{++} content in the needles (Clinton et al. 1994). Probably NO_3^- nutrition was an instrumental mechanism in soil alkalisation under poplars particularly if it is considered that pasture uptakes more NH_4^+ -N, although actual uptake depends on the NO_3^-: NH_4^+ ratio (Whitehead 1995). The accumulation of Ca^{++} and other cations was facilitated and a consequence of the change in pH. Smith et al. (1995) showed that Ca^{++} by it self is not important in ameliorating soil acidity, if it is not accompanied by a strong complexing anion to complex and mobilise the exchangeable Al and saturate the exchange sites with Ca^{++}.

Distribution of topdressed fertiliser did not contribute to fertility differences between the open pasture and poplar-pasture vegetation areas, as both the OP and PP received the same DAP fertiliser inputs in August. The higher Ca^{++} status could also be explained by the fertiliser applications of superphosphate which contains 20% Ca by weight (Parfitt et al. 1997). However, it could be possible that the superphosphate fertiliser distribution was affected if applied when the trees were in leaf, and consequently the PP area would receive less fertiliser inputs.

The recovery of topdressed fertiliser was about 53% of the amount applied by the fixed-wing aircraft. It was possible that drift and fertiliser bouncing out of the containers contributed to the lower recovery. Gillingham (1980) determined that the mean topdressing rate had a coefficient of variation of 48% with a fixed-wing aircraft.

The OP and PP areas were both grazed and thus exposed to nutrient transfer outside the system. The soils of grazed environments tend to acidify as a consequence of leaching NO_3^-, nutrient extraction and organic matter accumulation (de Klein et al. 1997). Changes in soil chemistry, including pH are also associated with animal nutrient transfer (Belisky et al. 1993). Hawke & Tombleson (1993) showed that with the exception of available Ca^{++}, soil pH, available K^+ and Mg^{++} were higher close to radiata pine shelterbelts resulting from animal transfer. Also it cannot be discarded the nutrient transfer of the poplar itself, not only from deeper soil strata, but from the wider root domain (related to lateral root length) into the crown domain (where leaf litter deposition would take place).

At Pohangina Hill 1, occasional observation of animal behaviour and the measured pasture cover (Guevara-Escobar 1997), indicated that animals preferentially grazed the OP area although they camped close to some trees (not considered in this study) at the edges of the OP and PP areas. Evidently, animal behaviour and fertility transfer needs further examination to identify the role of these factors, if any in influencing soil pH under poplars.

4.5.2.2 Soil mineral pools: C and N

Organic C and N have been reported to be higher in oak-pine or radiata pine forest soils than in pasture soils (Entry & Emmingham 1995, Griffiths et al. 1997, Parfitt et al. 1997, Yeates et al. 1997). However, for the sites described here, C and N for the PP soils were either similar or in the case of N slightly lower than the OP soils, reflecting the small N inputs from the legume component of the sward under the trees (see section 5.5.3.1). Power et al. (1998) also found no differences between open pasture and a range of N-fixing *Acacia melanoxylon* planting densities in agroforestry sites of the North Island of New Zealand. However, C (71.3 and 66.1 t ha^{-1} for open pasture and 500 sph) and N (5.3 and 4.6 t ha^{-1} for open pasture and 500 sph) pools in the work of Power et al. (1998) were approximately double to those reported in the present work.

The C:N ratios in topsoil were comparable to soils under pasture vegetation reported by Griffiths et al. (1997) in the U.S.A. at a similar latitude (44° N) and for the study by Giddens et al. (1997) in the Pohangina Valley and other New Zealand studies irrespective of the presence of poplars (Blackmore et al. 1987, McIntosh et al. 1997, Giddens et al. 1997). The relation found between the soil organic C and total N was also comparable to that reported by McIntosh et al. (1997) across a range of soil types for the open pasture vegetation.

Despite the large differences in the form and pattern of litter return, soil pH, exchangeable bases, pasture accumulation, N-fixation, soil temperature and moisture, total C pool size in the soil at Pohangina Hill 1 was similar, suggesting that C turnover was comparable between the OP and PP systems. However, on closer consideration, there are potentially large differences in the pools and fluxes of C through the respective systems. Although poplar leaf and grass litter could be expected to be different, the additional tree debris from more lignified material (i.e. branches) would decrease the decomposition rate. Alternately, the higher soil pH of the PP area would reduce the bonding between organic constituents and clays, resulting in release (solubilisation) and mineralisation of organic matter (Curtin et al. 1998). The net effect would be higher than expected decay rates in the PP area.

When considering soil restoration after erosion, the differences in C fluxes through the soil C pool and the amount of C in the biomass of the two systems must also considered. Assuming a typical 2 t DM ha^{-1} pregrazing standing pasture biomass for the OP and using the standing root biomass values (13.67 t DM ha^{-1}) in mid spring presented for low fertility hill country pasture by Saggar et al. (1997), total shoot and root pasture biomass in late spring was estimated at 15.7 t DM ha^{-1}. For the PP area, poplar standing biomass components were estimated using the equations based on diameter at breast height (DBH) for *P. deltoides* at 400 sph age 8 presented by Lodhiyal et al. (1995). Total above ground standing biomass for the poplars (37 sph age 29) was estimated at 29.0 t DM ha^{-1} and root biomass at 7.7 t DM ha^{-1} giving a total of 36.7 t ha^{-1}. Conservatively, pasture understorey biomass was considered to be 50% of the value calculated for the OP. Total standing biomass was estimated at 44.6 t DM ha^{-1} for 29+year old poplars at 37 sph. Singh (1998) reported 49 t ha^{-1} the total biomass of 10 year *old P. deltoides* at 1111 sph growing in saline plains in India. Although the estimate obtained for poplar foliage biomass (2.5 t ha^{-1} from Lodhiyal et al. 1995) for Pohangina Hill 1 is an underestimate of the autumn litter fall (3.1 t ha^{-1}), use of these equations suggested that since the trees were planted, the PP system had higher total C accretion than the OP. The difference in total organic matter (represented by the soil C and the standing biomass) between the two systems is more relevant if the PP site was less well developed, due to greater disturbance, at the time of planting,

The lower total C values at Pohangina Hill 2 could be a reflection of the lower fertility (N and P) status of the PP in comparison to the OP area. However, lower fertility influences the rate of C accretion (Murata et al. 1995) but not the quantity, which is governed by climate variables (Jenkinson 1990). The C:N ratio of the organic substrate is frequently used to predict the rate of decomposition: the larger the C:N ratio, the slower the rate of decomposition (Melillo et al. 1982). Pohangina Hill 1 and the Ballantrae sites showed similar ($P>0.05$) C:N ratios for the OP and PP areas, but not the Pohangina Hill 2 site. Thus, it is possible that the maximum C pool size for steady state in the Pohangina Hill 2 site had not yet been reached or simply was lower due to a greater degree of degradation or by the higher soil temperatures during winter-spring in comparison to Hill 1 (see section 5.4.2.2). If equilibrium pool size is climate controlled, then the pool size will be similar. However, if litter quality and input rates also affect the pool size, then Pohangina Hill 2 could be lower.

4.5.2.3 Available P and S

Plant available P was very low for both OP and PP plots in comparison to intensively farmed sites (Ghani et al. 1996) with higher fertility (30 mg available P/kg soil). However, the concentrations were within the range of hill country soils with open pasture in the Pohangina Valley (6 mg available P/kg soil) examined by Giddens et al. (1997). The differences in plant available and total P between the OP and PP vegetation areas were small in magnitude and could be attributed to a number of factors. Olsen P is reduced by high concentrations of Ca^{++} after liming and constitutes an artefact of the technique (Sorn-srivichai et al. 1984). How biased the Olsen P was in the present experiment was not determined. In general, the highest Olsen P concentrations were found in soils with low pH, 45 mg/kg @ 5.4 pH in the 0-20 mm soil stratum of the PP, 23 mg/kg @ 4.9 in the 0-20 mm soil stratum of the OP and 20 mg/kg @ 5.5 pH in the 0-75 mm soil stratum of the OP. These values contrast with 13 mg/kg @ 6 pH in the 0-75 mm soil stratum of the PP. Surprisingly the Ca concentration in the 0-20 mm and 0-75 mm strata of the PP area were identical (1125 mg/kg). This implies that soil pH depends not only on calcium concentration and that plant available P actually was higher in the superficial 20 mm regardless of the precipitation of calcium phosphates in the Olsen extracts (Sorn-srivichai et al. 1984) in the 0-75 mm soil stratum samples.

Increased plant available P (exchangeable P) resulting from pH change (Sorn-srivichai et al. 1984, Roberts et al. 1996) could be responsible for the comparable available P values for the OP and PP areas in most of the sites examined considering that an unknown P pool exists within the woody tree biomass. However, under *P. radiata* agroforest, plant available P increased (Hawke & O'Connor 1993) by dissolution of fluorapatite due to lower pH values while organic and inorganic P decreased (Perrot et al. 1995). Initial P mineralisation should decrease the total P pool and favour plant uptake, which in turn should limit increases of available P as well (Wheeler 1997). In the *P. radiata* agroforest pasture growth was depressed and plants could not make use of the extra P, whereas in the present study such accumulation was not evident due higher pasture or tree growth.

Other possible explanations for the lower P values in the PP area were 1) Fertiliser spread, 2) poplar nutrient dynamics and competition, or 3) animal transfer. If fertiliser applications normally occurred during winter then small differences in fertiliser spread should be expected between the OP and PP areas. However, in the summer with the trees in full leaf there might be big differences in fertiliser spread. Reduced P in the PP area could be the result of P uptake and retranslocation by poplars (Singh 1998) since P differences arise from the superficial soil stratum and not from depth. P concentration in soil will decrease as a consequence of a dilution effect by the lower retranslocation of K, Ca and Na than P in the poplar foliage (see section 5.4.1.16). On the other hand, pasture accumulation and utilisation was higher in the OP area (see 5.4.1.9) suggesting that animals must have higher P accretion in OP pastures only than in PP areas only. However, in this study, the OP and PP were not physically delimited and animals could move back and forth between the areas. Nevertheless, evidence of animal transfer effects due to camping close to the trees, as suggested by Giddens et al. (1997), were not found on the sites examined since P concentrations were always similar or lower in the PP vegetation area. The nutrient transfer away from the PP vegetation and into the OP area or to camps is another factor that should be considered, since P requirements in New Zealand are largely regulated by P transfer in animal faeces (Cornforth 1994).

The pool size of plant available S was similar across all the sites (3.7 to 4.5 kg ha^{-1}) in the 0-75 mm soil stratum. The maximum size of this plant-available soil SO_4^{2-}-S pool at any one time in a tight S cycle of marginally S-deficient pastures has been estimated to be 6 kg ha^{-1} (Nguyen & Goh 1993). Although herbage content of S was variable across sampling dates it indicated that S was in short supply. Herbage S concentration was lower in June and September 1996 (2.0 and 2.3 mg/g DM) and higher in March 1996 and May 1997 (3.2 and 3.1 mg/g DM), average values for the OP area being higher than that for the PP area (2.9 vs. 2.4 mg/g DM) (see section 5.4.1.14). These values were slightly lower than the average (3.0 mg/g DM) in New Zealand pastures (Nguyen 1990). Contribution of subsoil S to pasture plants may be significant in some New Zealand soils (Gregg et al. 1977) but not in this case since SO_4^{2-}-S concentration was halved below the 0-75 mm soil stratum. Organic S results were similar and reflected low S status (Ghani et al. 1996), but this indicator is less affected by seasonal variation or fertiliser applications (Watkinson et al. 1991). Although decreased leaching under the poplars is a plausible option, it did not lead to S accumulation. It is possible that S inputs in rainfall and fertiliser are below pasture requirements and mineralsiation is not fast enough in these sandy soils. In any case S, as well as P, was a scarce resource in the system and likely to limit plant growth.

4.5.2.4 Soil physical characteristics

Total porosity of 60 m^3 m^{-3} implies good soil aeration (Gradwell 1968). Nguyen et al. (1998) indicated that animal treading negatively impacts on bulk density and soil porosity. However, the reported values of Nguyen et al. (1998) for steep inter track land were higher (71.2 m^3 m^{-3} for undamaged and 62.6 m^3 m^{-3} skid damaged land) than the 53.6 and 52.4 m^3 m^{-3} found for the OP and PP vegetation areas, respectively. The sandy texture of the Pohangina sites may account for a lower pore proportion when compared with fine textured soil of other studies (Gradwell 1968, Nguyen et al. 1998), and still provide good water movement in the soil profile. The pore size distribution and size in two soil strata (0-75 and 75-150 mm) was very similar in both the OP and PP areas. Therefore, the net effect of the tree as it influences rainfall, pasture growth, soil pH, etc., on soil pore function assuming the physical properties of the soils were similar at the time of tree planting was small. Alternatively, if the site was degraded, then the tree may offer a very effective tool for restoring "soil health". The sandy loam soil texture would also explain the similarity between the OP and PP areas in water stability of soil aggregates. The BD results were not in agreement with the reported lower BD in forest reserve soils when compared to pastureland (McIntosh et al. 1997), although Yeates (1988) found similar BD for *P. radiata* and pasture soils. Joshi et al. (1997) showed that BD increased and soil porosity decreased during the first eight years of *P. deltoides* plantations. In the later study, most of the changes were attributed to the previous clear-felled natural mixed broad-leaved forest and the increased susceptibility to erosion of nutrients that poplars could not prevent (Joshi et al 1997). In the Pohangina site it was likely that erosion continued during a number of years after the poplar planting and, combined with the animal treading and soil compaction effect, masked or retarded the positive effect of trees on BD (Alonzo et al. 1979, Young 1997).

4.5.2.5 Soil earthworm population

It was not clear why earthworm populations were similar or lower for the PP in comparison to the OP. Although the examined sites had different geology and erosion processes, the standard error of the mean for indicator invertebrate numbers and mass was of the same order of magnitude between the sites, suggesting that sampling was adequate. Pohangina Hill 1 showed lower earthworm populations (numbers and mass/m^2) in the PP at the two sampling dates, whereas Hill 2 was the opposite, numbers and mass/m^2 were higher for PP than OP. The contrasting results in the surveyed sites were attributed to the sunnier aspect of Pohangina Hill 2 in comparison to Hill 1 and the inherent nature of the erosion processes of the hills and their soil types. Pohangina Hill 2 had a lower fertility status when compared to Hill 1, but had a similar fertilisation history. Pohangina hills have a sandy texture whereas the Rongoiti soil is clayey and this was reflected in similar earthworm number/m^2 for the OP and PP areas. Yeates & Boag (1995) compared open pasture and *P. radiata* agroforests soil earthworm populations and associated lower earthworm populations under *P. radiata* with higher water retention, less macropores and lower saturated hydraulic conductivity. However, such relations were not found in the poplar-pasture systems reported here.

Lambert et al. (1996) reported an earthworm population (79 g/m^2) in Ballantrae during July 1994 for plots of low fertility, this was lower than the measurements made three years later in October for the open pasture and poplar-pasture (129 g/m^2 and 118 g/m^2, respectively). For the Ballantrae site, rapid shifts in system function were unlikely to occur due to fertility history

(Lambert et al. 1996) and probably it might be applicable to the poplar planting as well. Thus, the differences between studies were attributed to fluctuations in earthworm dynamics.

The poplar leaf litter offered plentiful material to support higher invertebrate populations when compared with pasture alone, particularly in the sites with mature trees. By the time of sampling, most of the leaf litter was comminuted and available for decomposition. However, the results indicate that other environmental factors, besides the presence of poplars, were implicated in earthworm populations since substrate was not a limiting factor (Lofs-Holmin 1983). Higher pH rather than Ca has been reported to increase earthworm numbers after lime applications (Haynes & Naidu 1998), but no relationship was found between earthworm number or mass and Ca or pH in the present study. The beneficial effects of earthworms in soil structure and organic material (Stockdill 1982, Blair et al. 1995) were not clear in the poplar-pasture areas in this study, and possibly were negated by factors such as animal treading (Nguyen et al. 1998). The higher invertebrate mass and numbers found in a poplar silvoarable system by Park et al. (1994) and Wilson & Wild (1994) were not found at all sites in the present study. Probably the earthworm populations in the PP vegetation area were dependent on site-specific conditions or temporal in nature.

The fertility stratification in the poplar-pasture topsoil (0-300 mm) suggest that the tree is redistributing nutrients in the system, from a large soil matrix and concentrating nutrients in the surface below the canopy after litter fall or fine root decomposition. Earthworms have the capacity to redistribute the nutrients accumulated in the superficial 20 mm to deeper strata. However, distribution of nutrients from the surface to deeper strata in the poplar-pasture was not as uniform as in the open pasture. A possible explanation is that earthworm dynamics are different from the open pasture and it will take longer under the poplars to re-redistribute nutrients. However, microclimate and litter quality should not be discarded as influencing factors on earthworm population.

4.6 Conclusion

Apart from soil pH and exchangeable bases, information from this work indicates that few differences in topsoil biophysical characteristics were evident between the open pasture and poplar-pasture systems at the 0-75 and 75-150 mm soil strata. Most importantly, soil pH was up to 1.2 pH units higher in the poplar-pasture. This was also accompanied by higher exchangeable Ca K Mg and Na concentration in soil of the poplar pasture. The tree impact on soil pH and exchangeable bases was more evident in the mature poplar stands. Small differences in soil total N and no differences in organic C were found between the open pasture and poplar-pasture. Plant available P tended to be lower in the poplar-pasture while S was similar between the two examined systems. Soils from the open-pasture and poplar-pasture were similar in soil bulk density, hydraulic conductivity, macroporosity, aggregate stability and texture.

It was not clear how the positive tree effects on soil physical structure and fertility reported in the literature were masked or modified by animal traffic, nutrient transfer, tree uptake. Because the soil in the poplar-pasture was younger in origin, the nutrient distribution, particularly plant available P in the soil apparently also was different. The comparatively lower or similar earthworm populations in the poplar-pasture may be the consequence of different patterns of litter deposition and the overall physical and chemical soil status. It was hypothesised that nutrient accumulation and cycling mechanisms were different, particularly after soil erosion event(s) and tree planting occurred in the poplar-pasture. Possibly after 29-40 years, the poplar-pasture had not attained a steady state and soil conditions still might improve with time.

Tree leaf litter probably was the main contributor to nutrient redistribution although animals could play a secondary role. It was concluded that decomposed tree litter has the potential to encourage herbage growth and this depends on the amount of nutrient mineralised in controlled conditions. Similarly, soil from the 0-20 mm stratum from poplars provided enhanced chemical conditions for legume growth resulting from increased pH, changes in nutrient availability and nutrient inputs from tree litter under glasshouse conditions. Poplar leaf litter was identified as one of multiple factors intervening in soil pH modification.

Planting trees on the poorly mineralised environment of slip scars may reduce the time of healing independently of the stabilising capabilities of the tree itself. Because many of the soil properties were similar between the poplar-pasture and open pasture vegetation areas, it was concluded that trees helped to restore fertility to a level comparable to that if erosion had not occurred. For the site with young poplars, it will require a greater time frame for physical and chemical changes to be evident, other than soil pH. Preferential nitrate uptake by poplars could be a major operating mechanism in pH increase in a young poplar-pasture system, but canopy shading and interception may also contribute as the tree stand ages.

4.7 References

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5 Microclimate and pasture production in a poplar-pasture system

5.1 Summary

This Chapter evaluated pasture production in a poplar-pasture system with respect to environmental factors that differentiate the system from the traditional hill country pastureland system. Two studies were conducted. One study comprised one-year measurements in 1996-97 at a site with 29 year-old mature poplars (density: 37 stems/ha (sph)). Canopy closure ratio (CCR) was determined by image analysis. In addition to monthly pasture accumulation (PA), topsoil temperature and moisture (θ), photosynthetically active radiation (PAR) in the poplar-pasture (PP) and open pasture (OP) areas was measured. The validity of the concept of single-tree influence circles was tested for topsoil water. Pasture botanical composition and chemical content were assessed approximately every three months. Shed leaf biomass and chemical content of poplar foliage and leaf litter was also determined. The other study was conducted at four sites with poplars of age 5, 29, 29 and 40 years during the spring 1997 (density: 50-100, 37, 40 and 40 sph). Measurements included PA, botanical composition and chemical content, topsoil water, and temperature under the PP and OP areas.

In the first study, CCR was 70% and average PAR directly below the tree canopy within the 600 – 2200 time period was only 20% of the PAR in the OP area. Nevertheless, mean of maximal instant PAR within the 1400 – 1500 time period was 823 μmol m^{-2} s^{-1} for the OP and 697 μmol m^{-2} s^{-1} for the PP vegetation areas from December to March. With the exception of June to August, soil temperature was consistently lower in the PP area during the year. Maximum differences (2.8-3.5°C) were recorded during the summer. Annual θ means were different for the OP (43% v/v) and PP (37% v/v) areas in the most superficial soil stratum (0-150 mm). PP topsoil (0-150 mm) was drier in January, May and June, but θ was similar to the OP area in other months. Variation in θ around the trees was significant but small in magnitude to modify pasture production. The variation was attributed to uneven shading by individual trees. Rainfall was reduced to 86 and 67% from the regional average during 1996 and 1997, respectively. PA directly below the poplar canopy was 6.2 t ha^{-1} yr^{-1} or 60% of that measured in the OP area. When canopy gaps were accounted for potential understorey pasture accumulation (UPA) was estimated as 71% of that in the OP. Using the legume content in the sward, N-fixation in the PP area was estimated as 54% of that occurring in the OP. The PP area had slightly lower grass percentage at the expense of higher comminuted tree debris material. Legume and other species percentage (herbs and weeds) were similar between the OP and PP areas, although actual yields were always lower in the PP area. Botanical as well as chemical composition of pasture had seasonal variation. Pasture growing in the OP area generally had higher feed value in terms of crude protein (CP), metabolisable energy (ME), soluble sugars and starch (SSS) and *in vitro* digestibility (IVD). The worst pasture quality in the PP area was found March and the best in September-November. Nonetheless, spring grown pasture from the PP area had

higher CP: ME ratio. Poplar leaf fall was 3.1 t ha^{-1} during autumn and resulted in a decrease in PA in the following months by occluding sunlight. Retranslocation of N, P K and S in poplar leaf was estimated at 30.3%, 43.5%, 36.8% and 42.7%, respectively. Poplar foliage had better feed value and higher K, P and Zn content than leaf litter.

In the second study during late spring, differences between the OP and PP area were identified mainly in the sites with mature poplars. Soil temperature was lower (up to 3.6°C difference) while θ was higher (up to 12.2 %v/v in the 0-150 mm stratum) in the PP area. PA in the PP area was only 40% of that in the OP in sites with mature trees. The site with young poplars showed small differences in soil temperature and θ while PA was similar between the OP and PP areas. Although low fertility pasture species dominated the sward, *L. perenne* and *T. repens* were able to contribute 15-20% and 12-14%, respectively of the botanical composition in the PP area with mature trees. However, PA was lower for these two species in the PP area. Feed value at this time was comparable between the OP and PP areas and only small differences were found in SSS, IVD and ME, but not consistently in all sites. With the exception of one site with mature trees, the calculated ratio of CP: ME was higher for the pasture growing under the shade and represented a net CP surplus in the PP pasture. With the exception of the site with young trees, the K:Na ratio was different in pasture from the OP and PP areas.

The consistently lower PA under the poplar canopy was attributed to shading but its influence on the botanical composition was not definitive and had a seasonal recovery to the proportion found in the OP area. The poplar canopy directly decreased available rainfall to the pasture understorey, but preserved a more constant θ status. The tree effect had a dynamic and rather heterogeneous influence that was measured as the variation in soil water around the trees and demonstrated by images of the projected canopy area. These results indicated that shade, and not θ, limited pasture understorey production. Management options should be developed considering that light and not moisture was the limiting factor for pasture production and that the poplar canopy only had a decisive effect on PA in sites with mature trees. The high CP:ME and K: Na ratios in the pasture understorey during spring may have nutritional or palatability consequences. Leaf litter, fresh or senesced had enough nutrients as to support animal maintenance requirements.

5.2 Introduction

Grassland is the predominant component of New Zealand agriculture. Sustainability has been questioned in some hill areas of the country (Lambert et al. 1996), mainly as a consequence of historical erosive events (Hicks 1995) and poor matching of agricultural activity to the land use capability (Eyles & Newsome 1992). Widely space-planting of poplars has been used to prevent or limit the extent of erosion on hill country grasslands (van Kraayenoord 1993). This practice allows the pastoral land use to be retained (Ong & Black 1994) without requiring large financial resources, or limiting farm income in the short term, as opposed to blanket forestry (NZMF 1995). However, it has been suggested that poplars growing on hill country grassland compete for moisture (Gilchrist et al. 1993) or other resources.

To the extent to which poplars restrict pasture growth, composition, nutritive value and the relationship between poplars and soil water and temperature status, have not been comprehensively investigated in a poplar-pasture agroforest. Because the poplar-pasture has a fodder contribution, the leaf, leaf fall feed value, leaf fall yield also needed exploration. This paper compared pasture accumulation and edible tree material production of a poplar-pasture association and open pasture considering the aforementioned pasture and fodder aspects.

Given the major implications of soil water (θ) to land stability (Kelliher et al. 1995, O'Loughlin 1995) and pasture growth (Thornley 1996, Mohtar et al. 1997), there is a compromise between two objectives when poplars are planted. Quantification of θ within the domain of pasture development will help understanding of water relationships of tree-pasture associations and optimise pasture production without further impairing the environment from soil erosion. The relationship between pasture production and θ in the topsoil of open pasture and poplar-pasture areas was also explored.

The investigation was separated in a *'main study'* that examined broad characteristics of the poplar-pasture system in one site and then, a *'late spring study'*, which used four sites focusing on the major findings of the *'main study'*.

5.3 Material and Methods

Information is reported from a main study at a single mature poplar-pasture site. Afterwards, the major findings were compared during two months in spring with another two mature sites and one site with young poplars. Spring is the season when pasture growth is greatest since temperature and moisture are not limiting and also the shade effect in the poplar-pasture will be at it highest. The studies were named *'main study'* and *'late spring study'*. For the mature poplar sites, the significant differences identified cannot be directly attributed to management, since they were not replicated and no information before tree planting occurred was available.

5.3.1 Main study

5.3.1.1 Site description

A mature stand of *Populus deltoides* clone I78 was chosen with adjacent open pasture area on the same hillslope. Poplars were widely spaced at 37 sph (stems per hectare) and at least 29 years old according to photographic records and increment cores (see section 3.3.2.2). Beef cattle and sheep grazed the block and had free choice of grazing under or away from the trees. During the measurement year, the area was grazed seven times, 7-15 days/grazing at 34-50 sheep units/ha (su/ha). The site was located on a livestock farm of the Pohangina Valley, New Zealand (longitude 175°53'E, latitude 40°08'S, 250 m above sea level (asl.)). Average annual rainfall was 1200-1300 mm (Rijkse 1977). The site had experienced slip erosion and trees were planted to stop the process. The hill had an adjacent area of open pasture. The hills had a north-westerly aspect (290-300°) with a 20-25° slope. Recent fertiliser history consisted of annual topdressings of 200 kg single super phosphate ha^{-1} during 1993 to 1995, 150 kg diamonium phosphate-13S ha^{-1} on August 1996 and 130 triple superphosphate-15S kg ha^{-1} on March 1997. Low fertility grasses dominated the hill's pasture species. Trees had a closed canopy (touching branches) but pasture was good and commercially grazed.

5.3.1.2 Sampling design

For monitoring, the area was divided into three blocks: lower, middle and upper slope sections. Four trees surrounded by other tree canopies were randomly selected within each slope section. Similarly, four positions were selected away from the influence of the trees in each block. These positions formed the pseudo-replicates for poplar-pasture (PP) and open pasture (OP) vegetation areas.

5.3.1.2.1 Pasture sampling

Pasture dry matter (DM) accumulation rate was estimated using the trim technique (Radcliffe 1974), at 1-month intervals from February 1996 to September 1997. The pasture accumulation (PA) and other values reported here for each month were measured during the last week of the month. Measurements corresponding to June 1997 were combined as June-July 1997 due to poor PA. One pasture cage (1.14 x 0.64 m) was placed randomly around each of the 12 selected tree at approximately half way between the tree trunk and the projected canopy edge, and in a corresponding open pasture positions. Quadrat samples (0.2 m^2) for botanical composition and feed quality unsorted sub-samples (Mackay et al. 1995) were taken at approximately 3-month intervals. Pasture sub-samples were bulked by block and environment and analysed for botanical composition and feed quality. Assessment of botanical composition was made by manually sorting and grouping into grasses, legumes, dead material, other species and tree debris. Feed quality of pasture only samples was assessed by near infrared reflectance spectroscopy (NIRS, Corson et al. 1998). Pasture mineral content was determined by digesting the plant material in nitric acid and then analysed by ICAP ES ARL 34000 (Lee et al. 1986). Two bulked samples (10 trees each) from fresh (cut from the lower tree branches) and recently senesced poplar leaves were analysed for feed quality and mineral composition in January and April of 1996 and 1998 following the above analytical methods. During the 1998 autumn shed leaf biomass was measured using five 2 m^2 chicken net-framed cages randomly located under the poplar canopy while the livestock were grazing elsewhere. Samples were collected approximately every 10 days.

5.3.1.2.2 Soil water sampling

Volumetric soil water (m^3 H_2O m^{-3} soil) was estimated using the Time Domain Reflectometry (TDR) technique (Soilmoisture Co. USA). Permanent TDR probes were vertically inserted and remained installed at each OP (one set) and PP (eight sets around the tree) position. Soil water (θ) was measured from 0-150 and 0-300 mm soil strata. The average slope of each position was measured in an up-down hill transect with six points using a 60mm electronic level for every position where TDR rods were inserted. TDR readings were made on each of 3 consecutive days per month, from January 1996 to January 1997.

The validity of the concept of "single tree influence circles" (Zinke 1962, Boettcher & Kalisz 1990) was tested in the PP area. The PP TDR probe sets examined the spatial differences in θ under the vertical projection of the maximum canopy diameter of each of the selected trees. Values of θ were measured at each of two distances away from the tree stem (at the edge of the canopy, and half the distance between the previous point and the tree trunk), in a cruciform arrangement (downhill - west, uphill -east, north and south). For all these points, θ was determined for the 0-150, 150-300 and 0-300 mm soil strata. θ content for the 150-300 mm soil stratum was obtained using equation 1). The eight PP values of θ were averaged when compared with the OP vegetation area.

$$\theta_{z_{ii}-z_i} = \frac{\left(\theta_{z_{ii}} \times \omega_{z_{ii}}\right) - \left(\theta_{z_i} \times \omega_{z_i}\right)}{\omega_{z_{ii}-z_i}} \qquad (1)$$

where ω was the total soil volume at the z stratum to depth ii and i, given $i < ii$.

With the exception of May, the rate of change in soil water ($\Delta\theta$) in the z stratum was calculated from equation 2). The period of integration was given by t_b - t_a, which is defined by the interval between TDR readings with t being equal to time in days.

$$\Delta\theta_z = \left(\theta_{t_a} - \theta_{t_b}\right) \qquad (2)$$

where θ_{t_a}, and θ_{t_b}, were the mean volumetric water contents (v/v% soil) measured with TDR at times t_a and t_b, with $t_a < t_b$.

5.3.1.2.3 Soil temperature sampling

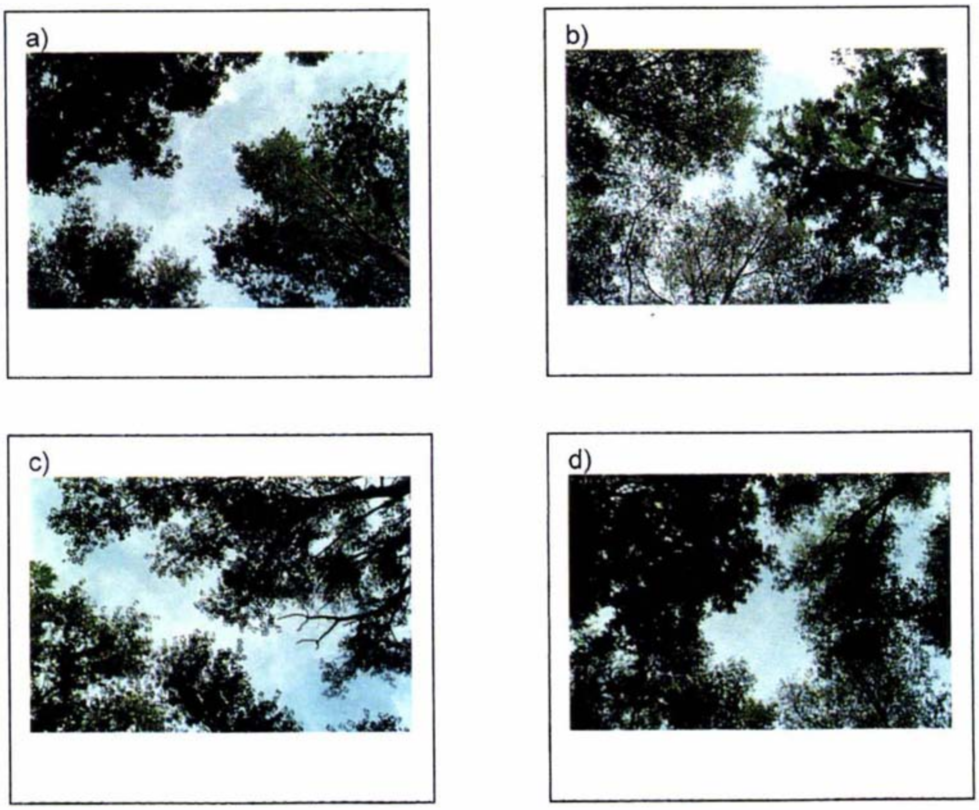
Soil temperature was measured at 100 mm depth in each OP and PP position approximately at the same hour during the morning monthly from February 1996 to September 1997. An electronic raingauge sited in the OP area measured accumulated rainfall and readings were recorded every month when pasture samples were obtained.

5.3.1.2.4 Light sampling

Photosynthetically active radiation (PAR) below trees in PP was measured from December 1996 to April 1997, using a Licor 1000 sensor that recorded average, maximum and minimum PAR values for 20-min. intervals and averaged for the hour. A reference value for PAR in OP was obtained from a nearby experiment (Ross Edwards personal communication).

The canopy closure ratio (CCR) was determined using digital image analysis. The proportion of tree canopy was reported as a percentage of the total area in the picture, which was considered a reasonable estimate of the projected tree canopy in the ground surface. From January to March 1998 digital photographs were taken facing vertically towards the poplar canopy using Kodak digital Science DC-50 and DC-120 cameras (Eastman Kodak Co. 1995, Figure 5.1). Shots were made at 10 metre intervals on a random transect across the slope of the PP area. Each transect consisted of 27 photos. A total of four sets of images were obtained. Digital images had 16.7 million colours (24-bit) and a 756 x 504 (DC-50) and 1280 x 960 (DC-120) pixel systems. Digital cameras were preferred to video camera recording (Knowles et al. 1997) because the latter only have a 16 bit 752 x 582 pixel interlaced system (Jähne 1997), thus having less edge definition (Jähne 1997, Wagner 1998) of leaves in the upper canopy. Files were downloaded into a PC system with a 166 MHz Pentium processor and 32 Mb of RAM. Image contrast was not modified to reduce blur as suggested by Wagner (1998) when analysing 256 grey scale images. Instead the 24-bit original matrix was used to determine the threshold between canopy and atmosphere pixels. Colour masking with Corel Photo-Paint 7.0 (Corel Corp. 1996) was used to systematically define a double threshold (Jähne 1997) for the colours pertaining to the canopy pixels. An image from every transect set was first selected and a colour filtering was applied by selecting a dark colour from the canopy and setting the colour selection threshold to ±10 steps (i.e. the 20 neighbouring colours in the 16.7 million spectra). The mask from the current selections was represented by a red tinted overlay making it easy to systematically identify canopy areas still needing to be masked. Two or three additional colour filters were usually needed to complete the colour mask. The mask protected only the pixels that fell within the colour range specified. The colour mask definition was saved to a file and then applied to the rest of the images in the set. This procedure established a standard colour boundary between the canopy and atmosphere pixels as remarked by Wagner (1998). The unprotected areas (atmosphere) were blanked to a single colour and then a binary thresholding operation was performed (Jähne 1997). Pixels were quantified using Sigmascan pro 4.0 (Jandel Scientific 1995).

Figure 5.1. Sample images of the poplar canopy at Pohangina Hill 1 site on 3 March 1998. Calculated canopy closure ratios for each of the images were a) 64.7%, b) 72.9%, c) 58.1% and d) 76.6%. Poplars were spaced at approximately 15 m.



5.3.2 Late spring study

5.3.2.1 Sites with mature trees

Two additional mature poplar-pasture sites were used to measure the most distinctive traits found in the site of the *'main study'*. One was located on the same farm at Pohangina (Pohangina Hill 2) and the other was on a commercial sheep farm at Rongoiti (longitude 175°44'E, latitude 37°30'S, 500 m above sea level). The Pohangina Hill 2 site had 29 year-old poplars widely spaced at 40 sph, grazed by sheep and set stocked to 10 sheep units/ha. The Rongoiti site had 40 year-old poplars widely spaced at 40 sph, grazed by sheep and set stocked to 8 su/ha. Average rainfalls at Pohangina and Rongoiti sites were 1200-1300 mm and 1150-1500 mm, respectively (Rijkse 1977, Campbell 1978). Sampling at the *'main study'* site (Pohangina Hill 1) was rearranged to match the procedures of the *'late spring study'*, at this time it was grazed by beef bulls and set stoked to 10 su/ha. Sampling was restricted to November and December and included pasture samples collected on each hill at five paired sampling pasture points protected from grazing by pasture cages. PA was measured each month. Botanical composition and feed nutrients were subsampled in December and analysed as described in the *'main study'*. Feed nutrient analysis samples were bulked into two samples per vegetation area and site. Botanical composition subsamples were hand sorted and the species identified. Volumetric soil water was measured at each OP and PP sampling point using one TDR probe set for 0-150 and 0-300 mm soil strata; probes were reinstalled each month. Soil temperature at 100 mm depth was also measured at each sampling position.

5.3.2.2 Site with young trees

Pasture traits, soil temperature and soil water were also sampled at a site with young poplars. An experiment was set up at Ballantrae AgResearch Hill Country Research Station (longitude 175°50'E, latitude 40°18'S) in a 20-25° northeasterly aspect slope and 300 asl. The long term mean annual rainfall is 1200 mm (Stevens et al. 1993). The experimental areas have received annual topdressings of 150 kg RPR/E/S ha^{-1} since 1991 with little or no fertiliser prior that date. The experiment was arranged as a randomised block design with two replicates and 5 blocks (n=20). The PP area contained *Populus spp.* at 50-100 sph and a complete pasture cover of low fertility grasses. The open pasture (OP) area was dominated by low fertility grasses as well (Stevens et al. 1993). The blocks corresponded to the downhill gradient. For each replicate and block, one sampling position was set up as in the mature poplar sites to measure the same traits. One pasture cage was under the canopy of each of the five sampling position of each replicate. Feed nutrient analysis samples were bulked into two samples per environment and replicate (n=8).

5.3.3 Statistical analysis

Soil water data from the *'main study'* was analysed as a split area in time using the GLM procedure of SAS (SAS Institute 1997). Soil water comparisons between the OP and PP areas were determined by ANOVA and one degree of freedom orthogonal contrast using the GLM procedure of SAS (SAS Institute 1997) for each individual month (Steel & Torrie 1980). Soil water values from the PP area were pooled by aspect and distance from the tree and then compared with the OP soil water values. Soil temperature, PA, botanical composition, feed quality variables and mineral content of pasture and poplar material were analysed individually for each month with a series of paired t-tests. In addition, average values of soil water (pooled for aspect and distance from the trunk) and soil temperature were used in a covariance model for PA. Significance of all preplanned comparisons was obtained with Fisher's protected LSD test for each month from the split in time test (Steel & Torrie 1980). The α level was set at 0.05.

Correlation functions were established using the CORR procedure of SAS (SAS Institute 1997) to establish the relations between the measured variables in each of the OP and PP areas. More specifically, the relations between botanical composition, and chemical composition, soil water and temperature were explored.

For the *'late spring study'*, data from the Pohangina and Rongoiti sites were analysed using paired t-tests performed with GLM procedure of SAS (SAS Institute 1997) for each site. Data from the Ballantrae experiment was analysed as a completely randomised block design to determine the statistical significance of the effects (Steel & Torrie 1980). Regression equations for feed quality components were established using the proportion of botanical components for OP and PP areas. The significance level was α=0.05 in all cases.

5.4 Results

5.4.1 Main study

5.4.1.1 Light

Daily average PAR directly under the poplar canopy in the poplar-pasture area (PP) ranged from 10% to 60% of the incoming radiation for open pasture (OP). The mean of average instant PAR within the 600 – 2200 time period was 347 μmol m^{-2} s^{-1} for the OP and 88 μmol m^{-2} s^{-1} for the PP vegetation area from the December solstice through to the March equinox of the 1996-97 season. During this period the sun's angle at transit decreased from 70° in December to 48° in March and so did PAR. For the days 22 to 25 December the mean of the averaged instant PAR was 122 μmol m^{-2} s^{-1} and for the days 19-21 March was 75 μmol m^{-2} s^{-1} under the shade of the trees. Nevertheless, the shading pattern of the tree canopy allowed sunflecks. The maximal instant PAR recorded for any given time integration (1 hour) under the trees was regarded as mostly sunflecks, since the value was close to OP instant PAR values. The mean of maximal instant PAR within the 1400 – 1500 time period was 823 μmol m^{-2} s^{-1} for the OP and 697 μmol m^{-2} s^{-1} for the PP vegetation areas from December to March. Analysis of the digital images determined a CCR of 70% (13 % standard deviation) before autumn leaf fall commenced (Figure 5.1). The CCR suggested that the maximum ratio of OP:PP PAR was related to the degree of canopy closure. If sunflecks were disregarded, it could be reasonably assumed that the maximum average PAR that could reach the pasture canopy in the PP vegetation was around 60% of that in the OP at the hour of maximum sunniness (1400-1500). However, the mean of average instant PAR directly below the tree canopy within the 600 – 2200 time period was only 20% of the PAR in the OP area.

5.4.1.2 Soil temperature

Soil temperature for PP was lower than for OP and followed a seasonal pattern. A change in the pattern of soil temperature in the PP area was observed in relation to the approximate time when the trees were in leaf (Figure 5.2). Maximal soil temperature for PP was reached in December 1996 (16.9°C ±0.2) and for OP in January 1997 (20.2°C ±0.4) and minimal values in June-July 1997, 7.4°C ±0.2 and 8.1°C ±0.3, respectively. With the exception of the winter months from June to August 1996 and June and July 1997, soil temperature was significantly different ($P<0.05$) between OP and PP. Maximum differences in the range of 2.8-3.5°C were recorded during the summer months, with the lower soil temperatures in the PP area being attributed to the poplar canopy shading. Thus, the range of variation during the poplar growing season in soil temperature in the PP was smaller than in the OP area.

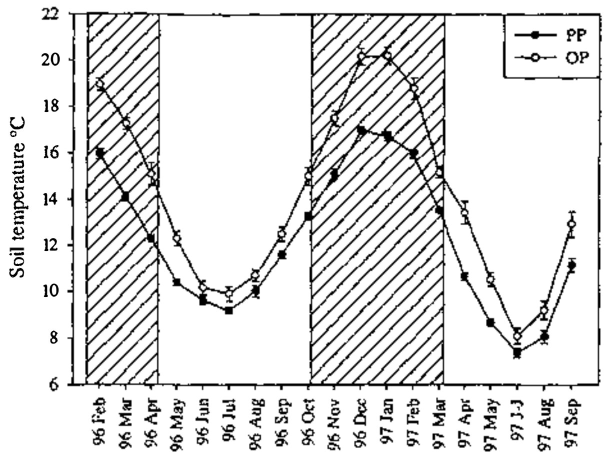


Figure 5.2. Soil temperature at 100 mm depth in the open pasture (OP) and poplar-pasture (PP) areas. Shaded areas represent the approximate period when the poplar trees were in full leaf. Line bars correspond to the standard error of the mean.

Table 5.1. Rainfall occurrence at Pohangina Hill 1 in the open pasture (OP) vegetation area. Periods of time correspond to the sampling interval.

		Rainfall (mm)	
	period	/period	/ day
1996	February	-	-
	March	58	2.0
	April	135	3.9
	May	112	4.0
	June	111	3.5
	July	117	4.2
	August	110	3.1
	September	48	1.8
	October	95	3.4
	November	89	2.5
	December	51	1.7
1997	January	49	1.5
	February	24	0.9
	March	48	1.7
	April	83	2.7
	May	7	0.2
	June-July	304	4.3
	August	55	1.6
	September	41	1.5

5.4.1.3 Rainfall

Annual rainfall from February 1996 (1069 mm) was 86% of the annual average (1250 mm) reported for the region (Rikjse 1977). The proportional rainfall from February to September 1997 (561 mm) also was 67% of the annual average, since 'El Niño' influenced the season 1997-1998. The majority of the rainfall deficit could be attributed the drier than average autumn and winter seasons, particularly to a dry spell of 42 days from late April to June (Met Service 1997). Table 5.1 shows the rainfall for the measured period. Rainiest months were June and July in both years.

5.4.1.4 Spatial variation of soil water in the Poplar-Pasture area.

Soil water (θ) around trees was affected by position relative to the tree trunk. The northerly aspect of the tree was the driest (32.8 % v/v ±0.4), and the southerly aspect the wettest (35.2 % v/v ±0.4) for the 0-300 mm stratum ($P<0.05$). The uphill (east) and downhill aspects around trees were generally similar ($P>0.05$). Tree aspect influence was different for the 0-150 and 150-300 mm soil strata (Figure 5.3). At the deeper stratum, variation around the tree had a smaller magnitude and was drier than the 0-150 stratum.

The differences found in θ around the tree were attributed to uneven shading by individual trees. The examined trees had a rather oval crown projection with 15.3 m in diameter, slightly smaller towards the northerly and downhill aspects (6.9 m ±0.5 and 6.4 m ±0.6, respectively) in comparison

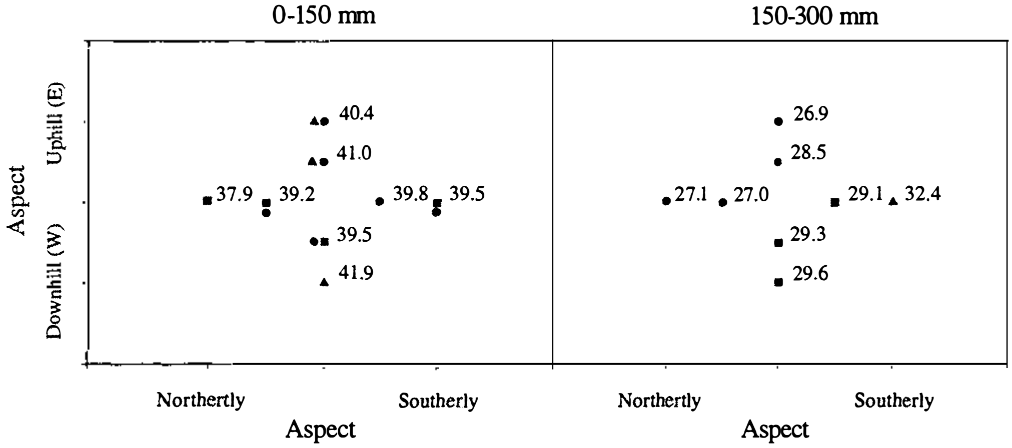


Figure 5.3. The influence of tree aspect on soil water (θ) at two soil strata in the poplar-pasture (PP) area in the north-westerly aspect of a hill in the Pohangina Valley. The cruciform arrangement represents the aspect's orientation and distance from the tree stem. The closer positions were between the tree trunk and the end of the projected canopy area, the farther positions were at the end of the canopy area. Values indicate θ averages (% v/v) for the period from February 1996 to January 1997. Northerly denominated °22 to the north-east from actual North. Positions around the tree stem represented with the same symbol were not significantly different (P<0.05).

with the southerly and uphill (8.3 m ±0.6 and 8.8 m ±0.6, respectively). Because the canopy was not completely closed (100%), there was opportunity for the north and downhill aspects to remain more exposed to desiccation. The small spatial differences detected in θ around the tree trunk throughout the year were not likely to add another source of variation to the soil water balance at other times or result in differential pasture growth capability under the tree crown domain. However, measurement of spatial variation within the crown domain was appropriate to compare the OP and PP soil water.

5.4.1.5 Change in soil water around trees

No significant differences (P>0.05) were found for the measured soil water change over one day ($\Delta\theta$) for tree aspect or distance from the trunk. Pooling the data for aspect and distance from the tree trunk showed that $\Delta\theta$ was different at the 0-150 and 150-300 mm soil strata for some months (P<0.05). Generally, the 0-150 mm stratum had a $\Delta\theta$ of greater magnitude than the 150-300 mm (P<0.05). The relationship between the vegetation area, the occurrence of rainfall during the measuring day and that the tree leaf status were explored to explain $\Delta\theta$ variation. The difference between soil strata was affected by rainfall occurrence (lower than 8 mm d^{-1}) only on some of the measured days under the trees (Table 5.2). The 0-150 mm stratum lost moisture at a higher rate because it was more exposed to evapotranspiration and drainage losses than the 150-300 mm stratum. However, when the poplars were in full leaf, the differences between soil strata were not evident. This was the result of the small number of samplings (n=192 per month) in some of those months when there no was rain in one day and when the other did. In August (leafless) and January (in leaf), it was possible to significantly (P<0.05) discriminate smaller differences because rainfall

Table 5.2. Rate of $\Delta\theta$ (% v/v d^{-1}) at two soil strata (mm) in the open pasture (OP) and poplar-pasture (PP) vegetation areas as measured every month during two consecutive days. Measurements were grouped according to the occurrence or not of rainfall during the measuring day.

	$\Delta\theta$ % v/v d^{-1}									
	No rainfall					With rainfall				
	0-150 mm		150-300 mm			0-150 mm		150-300 mm		
Month	PP	OP	PP	OP	SEM[1]	PP	OP	PP	OP	SEM
1996 FEB	1.84a[2]	2.05a	0.38b	0.24b	0.13	-	-	-	-	
MAR	-	-	-	-		1.79a	2.00a	0.33b	-0.63c	0.19
APR	1.75a	2.01a	-0.18b*	0.57b*	0.27	1.72a	1.73a	-0.20b	0.43b	0.27
MAY	nd[3]	nd	nd	nd		nd	nd	nd	nd	
JUN	2.00a*	2.93a*	-0.52b	0.02b	0.33	1.93a	2.65a	-0.55b	-0.58b	0.46
JUL	2.07a	2.35a	-0.05b	-0.65c	0.20	-	-	-	-	
AUG	-	-	-	-		1.28a	2.22a	0.19b	-0.15b	0.45
SEP	1.95a	2.30a	1.52ab	1.15b	0.20	-	-	-	-	
OCT	1.52a	2.84b	0.54c	0.03c	0.39	0.50a	1.12a	- 0.07a	-0.08a	1.04
NOV	1.26a	2.61b	0.67ac*	-0.44c*	0.41	0.86a	2.14ab	0.76b	-0.59b	0.60
DEC	1.26a	1.93a	0.34b	0.20b	0.25	-	-	-	-	
1997 JAN	2.10a	-1.41b	0.63a	-0.16bd	0.63	-	-	-	-	

[1] Pooled standard error of the mean.

[2] Within row and rainfall classification, means with the same letter were not different (P>0.05), letters with an asterisk (*) indicate a P<0.07 difference.

[3] θ was measured only on one day and $\Delta\theta$ was not determined.

conditions were similar, thus increasing the sampling number for that month (n=384). Also, it was possible that the poplar canopy buffered the magnitude of $\Delta\theta$, since the $\Delta\theta$ difference between the two profiles was smaller than 1.0 %v/v from September to December and higher than that on other months when drainage and evapotranspiration (*ET*) could have a greater impact on $\Delta\theta$.

5.4.1.6 Soil water in Poplar-Pasture and Open-Pasture

Differences between θ means for the vegetation area, soil depths and their interaction were significant (P<0.05) for some months, but only when soil temperature and slope were included as covariates. Over the 12 months the soil in the PP area was drier at the 0-150 and 0-300mm soil strata but not at the 150-300 mm stratum (Table 5.3, Figure 5.4). Mean θ was higher at 0-150 mm than at the 150-300 mm soil stratum (Table 5.3).

With the exception of January, May and June of 1996, monthly θ means for PP and OP at 0-150 mm soil stratum were similar (P>0.05) and this was supported by similar soil physical characteristics between the vegetation areas for this same soil stratum (see section 4.2.2.5). In January, May and June of 1996 soil at PP was drier (P<0.05) probably as a consequence of tree canopy or tree litter interference. Although not significant, PP at 0-150 mm also tended to be different during the month of March.

Mean θ for PP and OP at 150-300 mm were similar, except in January, July and September, of 1996 when the PP area was moister. As expected θ values for this soil stratum had smaller standard errors than the superficial stratum, mainly because it was less exposed to evapotranspiration and rainfall fluctuations. Also, it was anticipated that vegetation areas would be similar during the winter months since the trees were leafless. But, that was the period when most of the differences were observed in this stratum. For the 150-300 mm soil stratum apparently there was a distinct pattern between the vegetation areas and from that measured in the 0-150 mm soil stratum. Starting in June, θ was 5.7 v/v% greater in OP than PP at the 150-300 m soil stratum, and this was maintained until September; it then declined until both vegetation areas had the same θ in December. Visual observation of more frequent occurrence of small stones at the 150-300 mm soil stratum (Appendix II) suggested that the OP area had a lower moisture storage capacity and might recharge to a lower level during the winter.

5.4.1.7 Change in soil water in open pasture and poplar-pasture

When comparing the pooled data of 11 months, the mean $\Delta\theta$ was different ($P<0.05$) for the soil stratum depth effect, but not for the vegetation area effect ($P>0.05$). Mean $\Delta\theta$ for the 0-150 mm stratum was only different ($P<0.05$) between the OP and the PP areas in October, November and January in the absence of rainfall (Table 5.2). In October and November the OP area had a higher $\Delta\theta$ positive rate indicating water loss, whereas in January the rate was positive for PP and negative for the OP area, possibly as a result of subsurface flow. At the 150-300 mm stratum $\Delta\theta$ was different ($P<0.05$) in July and January on rainless days and in March, when it did rain. These rates were representative of the instantaneous differences between soil strata and vegetation area and it was not possible to compare them with any rate of monthly $\Delta\theta$. However, they indicated that the soil of the OP area experienced $\Delta\theta$ of greater magnitude than the PP area over short periods of time.

Figure 5.4 suggests that monthly $\Delta\theta$ of the OP and PP areas at 0-300 mm soil stratum had different rates, but from the end of September to end of November it was fairly uniform, particularly for the PP area. Thus, rainfall partitioning data obtained from 5 to 23 November on the same PP area using a different set of trees (see Chapter 3) could be used to predict soil water. The agreement between the data presented here and the *ET* coefficient modelled from the water balance was explored. The θ around the trees used in both studies was compared using a t- test. On 29 November 1996, θ at the 0-300 mm soil stratum was similar ($P>0.05$) for all the measured trees irrespective from the distance to the tree trunk (Table 5.4). This indicated that both sets of trees were representative of the same soil-water relations in that vegetation area. Although θ was different ($P<0.05$) at the 0-150 mm soil stratum, those values were not used to determine pasture *ET*, as they were likely to be indicative of micro-site conditions.

Table 5.3. Twelve-month soil water (θ) as % v/v means for the vegetation areas open pasture (OP) and poplar-pasture (PP), depth and their interaction.

Soil strata (mm)	Vegetation area OP θ % v/v	SEM[1]	Vegetation area PP θ	SEM	Depth θ	SEM
0-150	43.0 a[2]	0.7	37.9b	0.7	40.5a[3]	0.5
150-300	28.5c	0.7	28.7c	0.7	28.6b	0.5
0-300	35.8d	0.5	33.3e	0.5		

[1] Pooled standard error of the mean.

[2] Within the vegetation area effect, means with the same letter were not different (P<0.01).

[3] Within the depth effect, means with the same letter were not different (P<0.01).

Table 5.4. Soil water (θ) around the trunk of trees used for rainfall partitioning determination, 4 pseudo replicates and 3 samples and spatial variation of θ around tree trunks, 12 pseudo replicates and 4 samples. Data correspond to 29 November 1996.

	0-150 mm	SEM[1]	0-300 mm	SEM
	θ % v/v			
Rainfall partitioning trees				
2.4 m from tree trunk	45.9a[2]	1.6	35.7a	1.0
Spatial variation trees				
at ½ from canopy edge	40.4b	1.1	34.5a	0.7
at canopy edge	41.0b	1.1	34.6a	0.7

[1] Pooled standard error of the mean.

[2] Within column, means with the same letter were not different (P>0.05).

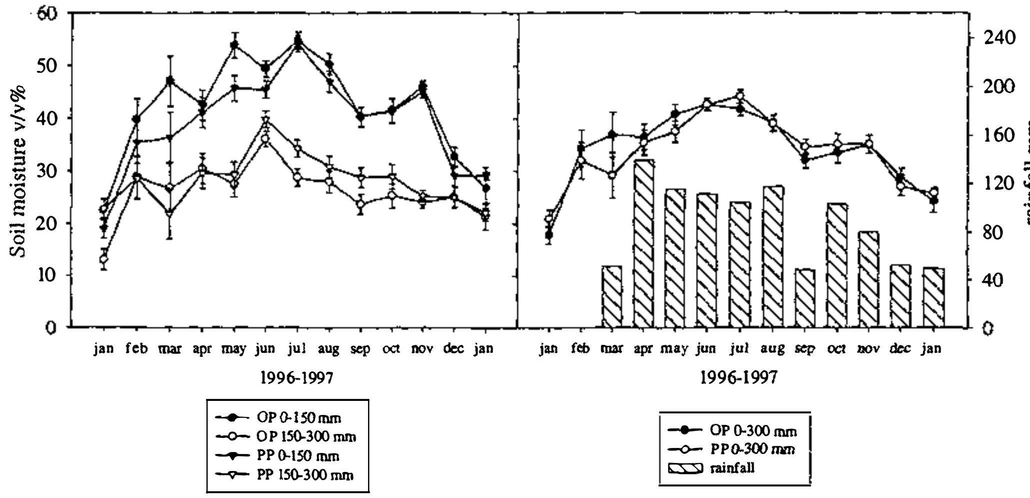


Figure 5.4. Soil water (θ) in the open pasture (OP) and poplar-pasture (PP) vegetation areas at 0-300, 0-150, 150-300 mm soil strata, the line bars represent the standard error of the mean. The 150-300 mm was derived as the volumetric difference. Monthly rainfall was recorded at the open field away from trees.

5.4.1.8 Integration of soil water with water balance model

The extrapolation of the *ET* coefficients calculated for November based on θ and rainfall data were not very accurate in the prediction of future or past values of θ, particularly for the PP vegetation area (See Chapter 3). For example, during the period from 29-11-96 to 27-12-96 total rainfall in the OP area was 51 mm, 62% occurring in two main rainfall events on the December 8 and 16. θ on 29-11-96 for the 0-300 mm soil stratum was 35.0 and 35.2 % v/v and on 27-12-96 was 28.8 and 27.0 % v/v for the OP and PP vegetation areas, respectively. Using the modelled evapotranspiration

(ET) loss of 2.4 mm d^{-1} (see Chapter 3) for the OP vegetation the water balance could be expressed using equation 3) and resolving for θ_z at $t+s=29$, the estimate of 28.8 % v/v was obtained.

$$\theta_{z_{t+s}} \times \omega_z = \theta_{z_t} \times \omega_z + \sum_{t=0}^{s} P - ET \times s \tag{3}$$

where P was rainfall in mm d^{-1}, ET evapotranspiration in mm d^{-1} $t=0$ was the initial time in days, $s=29$ the final time in days and z=0-300 mm.

For the PP vegetation, effective rainfall reaching the pasture canopy was calculated as a prediction for throughfall (Th) by the equation $Th= \beta_0 + \beta_1 P$ ($r^2= 0.98$ $\beta_0= -0.925$, $\beta_1= 0.759$) using measurements made during the previous month (see section 3.4.2). This model implied that any rainfall event smaller than 1.2 mm d^{-1} could be completely intercepted by the tree canopy. Thus the value of P was substituted by 36.6 mm which corresponded to Th and a maximum ET loss of 0.82 mm d^{-1} by the pasture vegetation only. Resolving for θ_z at $t+s=29$, 39.5 % v/v was an evident overestimate. The discrepancy could be attributed to higher than expected ET by the pasture understorey or poplars and the extrapolation of rainfall (21.2 mm) beyond the upper P (15.3 mm) value used to predict Th.

5.4.1.9 Pasture dry matter accumulation in open pasture and poplar-pasture

With the exception of the period from May to August 1996, DM pasture accumulation (PA) of the OP was higher ($P<0.05$) than the PP area (Figure 5.5). Lower PA in the PP was more evident in autumn at the time of leaf fall. For the period of March-May 1996 PA in the PP was 51.8% ±3.7 of that in OP area and during the same period in 1997 was only 39.9% ±2.3, whereas the average for other months was 60.6% ±3.9 of the OP area. Even during the winter months of June-August when shading and tree growth competition were minimal, PA in the PP area was 76.5% ±5.2 in 1996 and 47.0% ±8.3 in 1997 of that in the OP area. For the year starting on February 1996, the calculated total PA was 6.2 t ha^{-1} yr^{-1} ±0.3 and 10.6 t ha^{-1} yr^{-1} ±0.5 for the PP and OP areas, respectively. February 1996 had the highest PA rate, 48.9 ±3.4 and 74.7 kg ha^{-1} d^{-1} ±3.1 for the PP and OP, respectively. The lowest at 3.7 ±2.9 and 9.1 kg ha^{-1} d^{-1} ±2.9 for PP and OP, respectively, occurred in May 1996.

5.4.1.10 Pasture dry matter accumulation relations

From February 1996 to January 1997 soil temperature and θ were not useful in explaining further variation of PA not accounted by the month of the year, vegetation area (OP or PP) and the block factors ($P>0.05$). For this data set, the natural variation of soil temperature and θ at 0-150 mm was

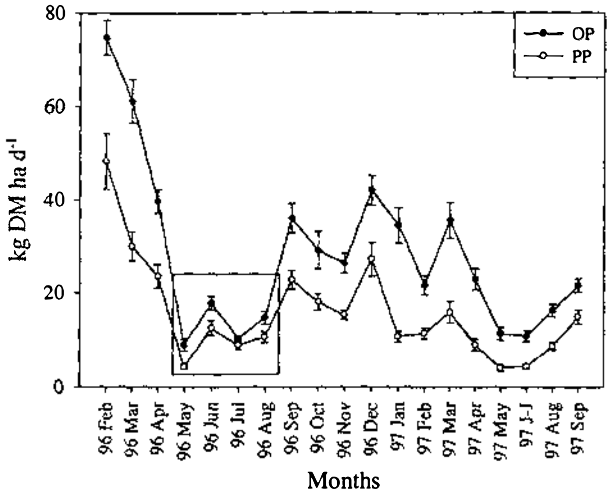


Figure 5.5. Pasture accumulation (PA) rate of hill pasture in open pasture (OP) and poplar-pasture (PP). Line bars show the standard error of the mean. The rectangle indicates the window in which the OP and PP had a similar PA (P>0.05).

Table 5.5. Results of regression analysis explaining pasture accumulation (PA) in the open pasture (OP) and poplar-pasture (PP) areas from February 1996 to January 1997 in the Pohangina Hill 1 site.

	constant	A[a]	B[b]	A*B	R^2
OP	58.2	-1.28	*-0.17*[c]	*0.05*	0.35
	-11.37		2.86		0.29
	73.88	-0.95			0.25
PP	53.7	-1.5	*-2.18*	0.15	0.21
	-10.83		2.35		0.18
	44.82	-0.62			0.11

[a] Soil water at 0-150 mm soil depth.
[b] Soil temperature at 0-100 mm soil depth.
[c] Coefficients in italics were not different from 0 (P>0.05).

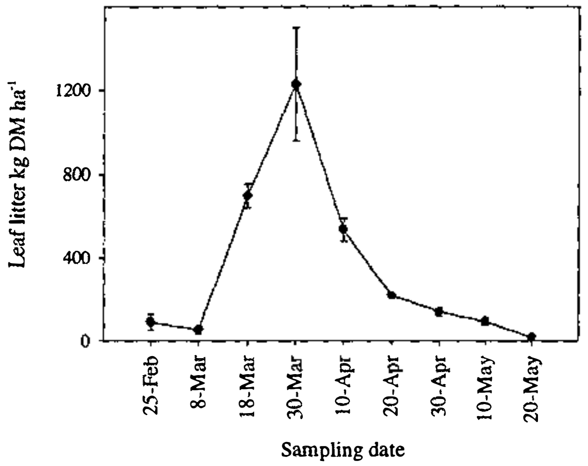


Figure 5.6. Poplar leaf litter dry matter (DM) accumulation during the autumn of 1998 in the poplar-pasture area. Line bars represent the standard error of the mean (n=5).

not big enough to affect PA within this domain. The relation between the PA and soil temperature and θ at 0-150 mm for each vegetation area was explored using linear regression of the February 1996 to January 1997 data, removing the block and month factors from the model (Table 5.5). In both the OP and PP areas, soil temperature or θ at 0-150 mm had a highly significant effect on PA (P<0.01). But when both variables were included in a single regression model for each area, soil temperature did not explain (P>0.05) any variation not already represented by θ at 0-150 mm. The interaction between soil temperature and θ at 0-150 mm was significant (P<0.05) for the OP but not the PP area. These results indicated that although θ might be a governing factor, the natural covariance between temperature and moisture could not be disentangled under field conditions, thus effects of each variable on each other and on PA were not independent.

5.4.1.11 Autumn litter fall

The lower PA rate during autumn and winter in the PP area was partially attributed to physical obstruction by shed poplar leaves. Physical obstruction modifies the microenvironment beneath the litter fall layer by occluding light, increasing moisture and temperature. Total leaf litter mass collected from 25 February to 20 May 1998 was of 3.1 t ha^{-1} (Figure 5.6). This period was typical of poplar leaf senescence in the area. Although leaf litter immediately depressed PA (March vs. April) the effect was transitory because leaf litter material rapidly disappeared under the pasture canopy.

5.4.1.12 Pasture botanical composition

Botanical composition was variable throughout the examined months for the PP and OP areas as indicated by a significant month by area interaction ($P<0.05$). Figure 5.7 shows the transient differences in composition between the PP and OP areas. Grass was the most abundant component for both areas. Low fertility species (*Festuca rubra*, *Agrostis capillaris*, *Anthoxanthum odoratum* and *Cynosurus cristatus*) were predominant over *Lolium perenne* and *Dactylis glomerata*. The grass proportion decreased and dead pasture material increased during the late summer-autumn periods (Jan 1996 and March 1997). Both March samplings took place during the initial phase of leaf fall. Significant differences in botanical composition ($P<0.05$) were measured before and after leaf fall on both seasons. In March grass was 70.5% vs. 83.3% in 1996 and 65.0% vs. 48.5% in 1997 for the PP and OP area, respectively and in winter was 67.5% vs. 82.5% in 1996 and 51.8% vs. 71.5% in 1997 for the PP and OP area, respectively. With the exception of the autumn of 1997, the PP area presented a lower grass proportion than the OP area mainly because of higher dead pasture and tree debris proportions. For the PP area, dead pasture material was predominant during autumn-winter rather than summer as in the OP area. In PP this condition probably resulted from delayed grass maturity due to tree shading. The tree debris was found in higher ($P<0.05$) proportion during winter mainly as comminuted leaf and branch particles intermixed with the grass. Evidence of leaf litter drift into the OP area was detected in the botanical components during the winter sampling of the second season.

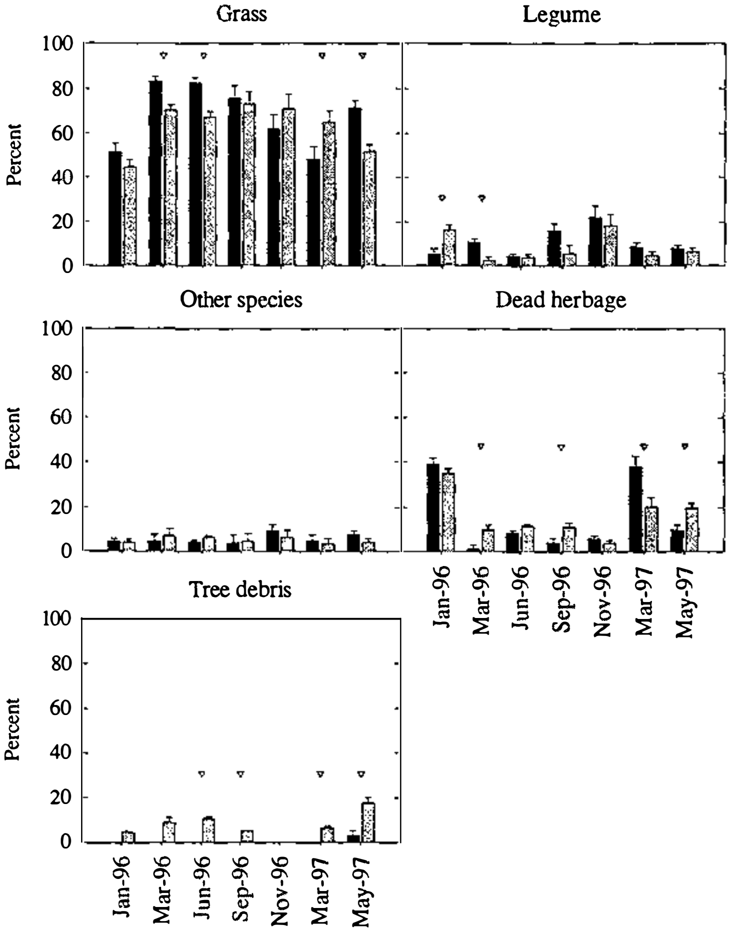


Figure 5.7. Botanical components as percent of pasture DM at the open pasture (black) and poplar-pasture (grey) areas. A triangle indicates a difference ($P<0.05$) for a group bar. Line bars represent the standard error of the mean.

However, this drift was assumed to have little repercussion on PA in the OP area.

With the exception of the two first sampling dates for 1996 (16.3% vs. 5.0% on January and 2.4% vs. 10.7% on March for the PP and OP area, respectively), the legume component was not significantly different between the areas (P>0.05). However, the OP tended to present higher values at all the sampling dates. As expected, a higher proportion of legumes was found in spring for both areas (September and November 1996). Legumes were mainly represented by *Trifolium repens* and *Lotus pedunculatus*. The maximum legume content obtained in November 1996 (18.5% vs. 22.3 % for the PP and OP, respectively) suggested that this plant component thrived adequately under the early stages of the shady season.

Flat weeds, thistles and other plants here described as 'other species', had a high variability and no statistical difference was identified between the areas. Tree debris material was found in samples of the PP area collected in and around the leaf fall event, and disappeared during the winter and spring. Samples from the OP area had none or very little tree debris.

5.4.1.13 Accumulation rate by botanical components

Grasses were the most important plant community in the sward when the PA rate was partitioned in the different botanical components (Table 5.6). With the exception of September and November 1996, grasses accumulation rate was higher in the OP area (P<0.05). Legume accumulation rate was similar and only lower (P<0.05) in the PP area in March and September 1996 and May 1997. A difference in other species accumulation rate was evident only in May 1997. Dead herbage accumulation rate only was substantially higher for the OP area in January 1996 and March 1997. September and November 1996 were the samplings when accumulation rates of the different (P>0.05) components were more similar between the OP and PP areas, although accumulation rate figures tended to be slightly higher for the OP area.

Table 5.6. Pasture DM accumulation (PA) rate[1] by botanical components in open pasture and poplar pasture areas at the Pohangina Hill 1 site during 1996-97.

	Grasses			Legumes			Other species			Dead herbage			
	OP	PP	SEM[2]	OP	PP	SEM	OP	PP	SEM	OP	PP	SEM	n[3]
						kg DM ha^{-1}							
Jan-96	39.4a[4]	21.9b	3.8	4.0a	7.7a	1.7	3.3a	1.8a	0.9	30.4a	17.1a	3.2	21
Mar-96	59.1a	16.4b	3.0	7.8a	0.6b	1.4	3.3a	2.0a	1.3	0.9a	4.0a	0.9	9
Jun-96	11.9a	6.3b	1.6	0.7a	0.4a	0.2	0.6a	0.6a	0.1	1.3a	1.0a	0.2	9
Sep-96	13.0a	10.0a	2.6	2.4a	0.8b	0.4	0.6a	0.5a	0.5	0.8a	1.5a	0.3	9
Nov-96	14.3a	12.2a	2.4	4.9a	3.0a	1.0	2.0a	1.1a	0.6	1.4a	0.7b	0.2	9
Mar-97	20.9a	6.8b	2.8	4.3a	0.6a	1.2	1.8a	0.3a	0.7	16.9a	2.4b	2.9	9
May-97	7.6a	2.1b	0.8	0.9a	0.3b	0.2	0.8a	0.2b	0.2	1.1a	0.8a	0.2	24

[1] Obtained averaging PA rate in the same way as botanical composition samples were bulked.
[2] Pooled standard error of the mean.
[3] Number of bulked samples.
[4] Within row, within botanical class means with the same letter were not different (P>0.05).

Table 5.7. Monthly estimates of N-fixation in the open pasture (OP) and poplar-pasture (PP) areas at the Pohangina Hill 1 site.

	OP	PP
	Kg N ha^{-1}	
Jan-96	4.4	8.5
Mar-96	8.7	0.7
Jun-96	0.8	0.4
Sep-96	2.7	0.9
Nov-96	5.4	3.3
Mar-97	4.8	0.7
May-97	1.0	0.3

Estimates of N-fixation were constructed using a conservative value of 37 kg N per 1 t DM of white clover (Crush 1987) and assuming that N-fixation was similar in both the OP and PP areas. Monthly (30 d) N-fixation for the OP and PP is shown in Table 5.7. Total N-fixation for the OP and PP was calculated as 53.4 and 28.9 kg N ha^{-1} yr^{-1} respectively, considering that the values for each sampling were representative of the interval between samplings.

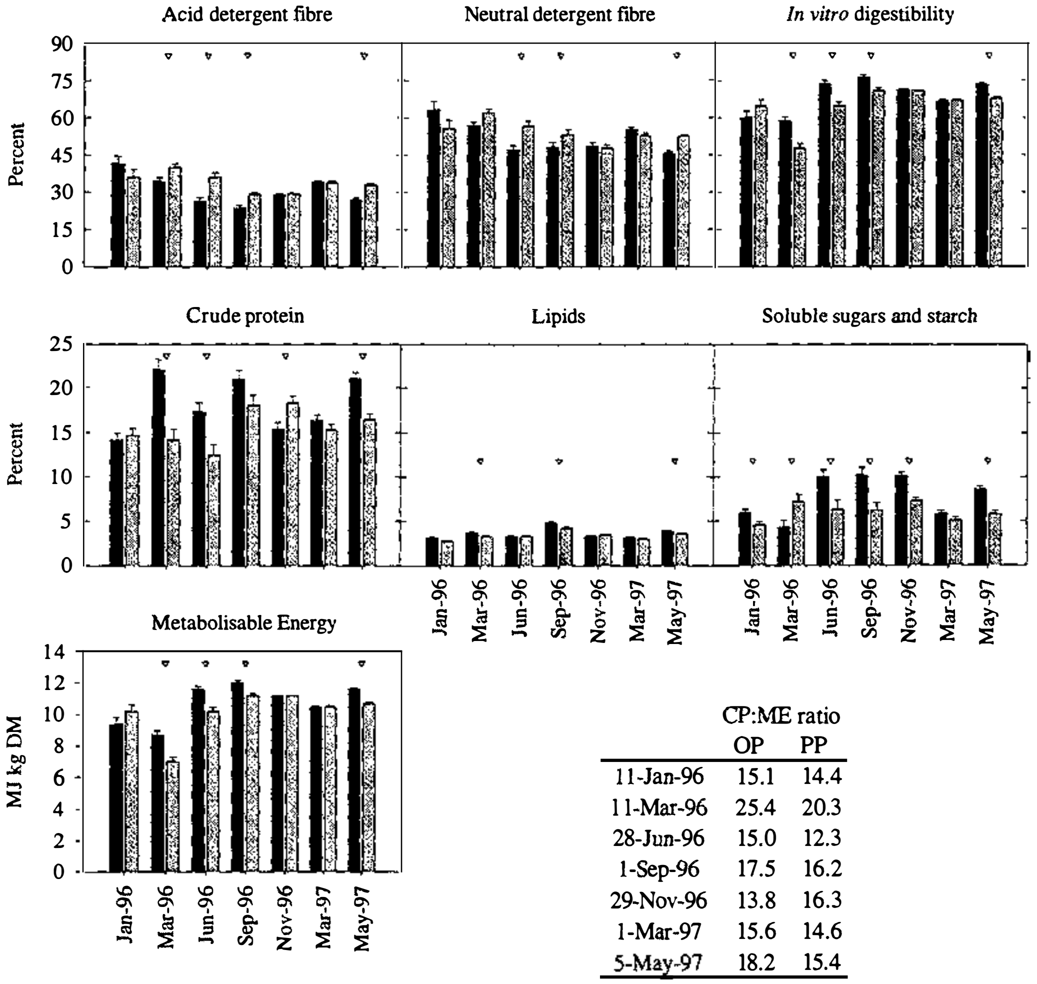
5.4.1.14 Pasture feed quality

The lowest nutrient values for both the OP and PP areas were found in January and March 1996 (Figure 5.8). In the former sampling, only soluble starch and sugars (SSS) were different for the OP and PP areas ($P<0.05$), and in the latter sampling all indicators were different between the areas ($P<0.05$), excepting neutral detergent fibre (NDF). In January 1996 feed quality was slightly better for the OP pasture and in March it was worst in pasture from the PP area. In March 1997 all feed quality indicators showed that the pasture from the PP area was of lower quality in all respects.

In the rest of the samplings (June, September and November 1996 and May 1997), feed quality was good or very good for both areas. The OP area was slightly higher in crude protein percent (CP), *in vitro* digestibility (IVD) and metabolisable energy (ME) in June and September 1996 and May 1997 ($P<0.05$). Also, the acid detergent fibre (ADF) and NDF fibre components were different during the winter (June 1996 and May 1996) and in September of 1997. Although the indicators suggest that OP had a better feed quality for most of the time, the difference between the areas was at the most 8.9% in IVD and 1.5 MJ kg DM of ME energy (both in June 1996). With the exception of the November 1996 sampling, the CP: ME ratio was smaller in the PP area (Figure 5.8).

Significant ($P<0.05$) correlation was found between some botanical components and feed quality indicators of pasture. The correlation analysis showed that the grass component correlated positively with lipid (r=0.39) and negatively with ADF (r= -0.45) and NDF (r= -0.34) content in the OP area ($P<0.05$) while having a positive conelation to SSS (r=0.45) content in the PP area ($P<0.01$). The legume content was only correlated (r= -0.32) with the lipid content in the PP area. Similarly, dead pasture had a negative correlation with CP, lipid, IVD and ME (r= -0.34, -0.51, -0.50 and --0.40, respectively) while having a positive correlation with the fibre components ADF and NDF (r=0.40 and 0.35, respectively). The 'other species' component was not correlated to any feed quality indicators ($P>0.05$).

The nutrient requirements of a 450 kg liveweight (LW) dry dairy cow gaining 1.0 kg LW/d were used to explore the nutritional balance of the examined pastures. Such an animal requires 8.2 kg DM feed intake with a nutrient concentration of 11.4 MJ ME /kg DM and 152 g protein /kg DM (AFRC 1993). Table 5.8 presents the DM intake needed to fulfill the ME requirement, and the deficit or surplus in CP when using the nutrient concentration of pasture in the OP and PP areas. For comparison, the IVD and N values presented by Hawke et al. (1993) for pasture growing under *P. radiata* at 50 sph are used in Table 5.8, as well as flatland dairy pasture typical of the region. N was converted to CP by multiplying by a 6.25 factor and IVD to ME using the linear relation ME=0.130 IVD+0.01 CP+1.09 (MAFF et al. 1984). During late spring (November-December), higher CP surplus resulted from the diets using pasture growing under shade of poplars as consequence of the higher CP: ME ratio at all sites.



	CP:ME ratio	
	OP	PP
11-Jan-96	15.1	14.4
11-Mar-96	25.4	20.3
28-Jun-96	15.0	12.3
1-Sep-96	17.5	16.2
29-Nov-96	13.8	16.3
1-Mar-97	15.6	14.6
5-May-97	18.2	15.4

Figure 5.8. Pasture feed quality in open pasture (black) and poplar-pasture (grey) areas. A triangle indicates a difference (P<0.05) for a group bar. Line bars represent the standard error of the mean. The inset table shows the ratio of units of crude protein (g kg DM) per unit of metabolisable energy (MJ kg DM) at the sampling dates.

Table 5.8. Amount of feed needed to fulfill the ME requirement (AFRC 1993) of a 450 kg live weight (LW) dry dairy cow gaining 1.0 kg LW/d and the consequent protein surplus or deficit resulting from using pasture from the open pasture (OP) and tree-pasture (TP) areas as basic feed. For comparison, data from a *P. radiata* agroforest at 50 sph. at Tikitere (Hawke 1993) and typical Manawatu dairy pasture are included.

	kg DM in ration		g CP in ration		Surplus g CP	
	TP	OP	TP	OP	TP	OP
Date	Pohangina Hill 1					
Jan-96	9.4	10.2	1383	1449	136	203
Mar-96	13.7	11.0	1946	2437	700	1191
Jun-96	9.4	8.3	1176	1439	-71	193
Sep-96	8.6	8.0	1550	1679	304	433
Nov-96	8.6	8.6	1568	1319	321	73
Mar-97	9.1	9.1	1398	1498	152	252
May-97	9.0	9.0	1479	1892	233	646
Dec-97	9.8	9.2	1850	1753	604	506
	Pohangina Hill 2					
Dec-97	10.4	9.1	1627	1475	380	229
	Rongoiti					
Dec-97	8.8	8.6	1787	1773	540	527
	Ballantrae					
Dec-97	9.7	9.5	1832	1596	585	349
	Tikitere					
Nov-87	8.7	8.7	2242	2057	995	811
	Manawatu					
Spring		8.1		1667		420

5.4.1.15 Pasture mineral content in open pasture and poplar-pasture

Pasture from the PP area had higher ($P<0.05$) content of Ca, Co, and Sr (Table 5.9). Sulphur content was lower ($P<0.05$) for pasture from the PP. The mineral content of pasture was different ($P<0.05$) at some of the sampled dates (Appendix IV). These differences were consistent since the interaction between vegetation area and date of sampling was not significant ($P>0.05$). Data from the November 1996 sampling and for Cd, Cr and Zn have to be discarded as contamination was suspected from soil or possibly galvanised shielding from the pasture cages.

Differences attributed to season included Al, Fe, K and Mo. Aluminium and Fe were lower ($P<0.01$) in June-96 than at other sampled times. Molybdenum was higher ($P<0.01$) at September-96 than at any other time. Potassium was higher ($P<0.05$) at the May-97 sampling than in other sampled months. The only potential inconsistency across the sampling dates and vegetation areas

Table 5.9. Forage mineral content combining four samplings for the open pasture (OP) and poplar-pasture (PP).

Mineral	OP	SEM[1]	PP	SEM	Mineral	OP	SEM	PP	SEM
				µg/g DM					
Al	485.5a[2]	39.8	515.3a	41.8	Mn	212.1a	21.8	152.7a	22.8
As	3.4a	0.1	3.4a	0.1	Mo	0.6a	0.1	0.5a	0.1
B	10.9a	0.8	13.0a	0.8	Na	1653.2a	213.2	1097.3a	223.6
Ca	5254.9a	341.9	6884.7b	358.6	P	3680.7a	204.4	3298.6a	214.3
Cd	1.5a	0.1	1.7a	0.1	Pb	3.0a	0.0	3.0a	0.0
Co	0.4a	0.1	0.9b	0.1	S	2926.9a	153.2	2408.6b	160.7
Cr	8.2a	2.0	12.7a	2.1	Se	6.2a	0.2	6.5a	0.3
Cu	12.2a	0.7	12.7a	0.8	Si	462.6a	16.9	506.2a	17.7
Fe	375.5a	21.1	439.2a	22.1	Sn	0.9a	0.1	0.7a	0.1
K	26836.0a	1550.6	24228.5a	1626.3	Sr	38.9a	2.8	59.7b	2.9
Mg	2061.4a	64.3	2194.9a	67.5	Zn	41.4a	3.6	62.3b	3.8

[1] Pooled standard error of the mean.

[2] Within row and mineral, means with same letter were not different ($P>0.05$).

Table 5.10. Calcium: Phosphorus and Potassium: Sodium ratios in the pasture from open pasture (OP) and poplar-pasture (PP) areas at different sampling dates.

	Ca:P			K:Na		
	OP	PP	SEM[1]	OP	PP	SEM
Mar-96	1.3a[2]	2.0b	0.1	18.3a	17.5a	4.6
Jun-96	1.5a	3.0b	0.3	17.8a	26.1a	4.1
Sep-96	1.6a	1.4a	0.2	18.6a	20.7a	8.6
May-97	1.4a	2.9b	0.4	26.8a	24.8a	4.8

[1] Pooled standard error of the mean.

[2] Within row and mineral ratio, means with same letter were not different ($P>0.05$).

of the analysed minerals was for K, because at the May-96 sampling the OP (3.6% ±0.27) and the PP (2.7% ±0.33) areas were different at the 0.06 α level.

With the exception of the September 1996 sampling, Ca:P ratios (Table 5.10) were different between the OP and PP areas ($P<0.05$). In the OP area the ratios were always below the recommended feed Ca:P ratio of 2 (van Soest 1994). The Ca:P ratio in the PP area was only lower than 2 in September 1996. K:Na ratios were not significantly different between the OP and PP areas (Table 5.10).

5.4.1.16 Poplar foliage and leaf litter feed quality and mineral content

With the exception of lipid content all poplar leaf feed quality indicators differed ($P<0.05$) between foliage and leaf-litter (senesced) material (Table 5.11). Differences were consistent for the two sampled years with the exception ADF, SSS, IVD and ME ($P>0.05$). CP, SSS, IVD and ME were higher in the foliage samples while fibre components and ash were higher in the leaf-litter samples. Poplar foliage feed quality was good and ME and CP content was comparable to that of the September-November PP forage. Poplar leaf litter had poor quality and the ME, CP and IVD were inferior to the March 1996 forage sample from the PP area, the worst of all forage samples examined. Mineral content in the foliage was higher for K, P and Zn ($P<0.05$). Calcium, Co, Cu, Mg, Mn and Na were different only at the $P<0.10$ significance level (Table 5.12). The amount of nutrients returned to the system in the poplar leaf litter was estimated from the leaf litter mineral content as 35, 3.1, 31, 6.2 and 59 kg ha^{-1} yr^{-1} of N, P, K, S and Ca, respectively.

Table 5.11. Nutritive content of poplar leaf material at summer (foliage) and autumn (leaf litter) of two years at Pohangina Valley.

		1996		1998		
		foliage	leaf litter	foliage	leaf litter	SEM
CP	%	18.5a	7.7b	17.5a	6.5b	1.05
Lipid	%	4.7a	4.7a	4.5a	3.9b	0.14
ADF	%	25.8a	45.7b	21.5c	38.3d	0.27
NDF	%	38.8a	58.4b	27.9c	44.8d	0.70
SSS	%	10.7a	<0.1b	13.0a	0.4c	0.28
Ash	%	10.1a	13.4b	8.9c	11.5d	0.19
IVD	%	74.2a	56.3b	75.7c	49.9b	0.61
ME	MJ kg	11.7a	8.8b	11.3c	7.4d	0.09

[1] Pooled standard error of the mean (n=8)

[2] Within row, means with same letter were not different ($P>0.05$).

Retranslocation of nutrients from leaves was estimated using the ratios of an immobile mineral to account for the variable amount of organic matter and nutrients that were withdrawn before senescence. Calcium was accounted in the estimates by dividing the nutrient: calcium ratio in the leaf-litter by the nutrient: calcium ratio in the foliage (Vitousek & Sandford 1986). Retranslocation of N, P K and S was estimated at 30.3, 43.5, 36.8 and 42.7%, respectively.

Table 5.12. Mineral content of poplar leaf material in summer (foliage) and autumn (leaf litter) of two years expressed as µg/g DM.

Mineral	foliage	leaf litter	SEM	Mineral	foliage	leaf litter	SEM
Al	157.3a	148.3a	47.44	Mn	155.4a*	206.1a*	11.62
As	2.3a	2.4a	0.13	Mo	0.3a	0.3a	0.02
B	50.9a	55.0a	1.80	Na	1072.8a*	783.8a*	85.57
Ca	15071.0a*	19247.0a*	1317.57	P	1929.5a	1083.0b	34.39
Cd	2.9a	2.6a	0.21	Pb	3.2a	3.3a	0.08
Co	3.5a*	5.0a*	0.50	S	3805.3a	2012.5a	400.95
Cr	4.6a	6.7a	0.94	Se	4.7a	4.1a	0.41
Cu	9.0a*	10.1a*	0.32	Si	251.3a	327.3a	36.43
Fe	162.6a	196.0a	34.01	Sn	0.6a	0.6a	0.02
K	22565.0a	10154.0b	1849.29	Sr	160.2a	211.3a	13.11
Mg	4776.8a*	3969.0a*	182.46	Zn	158.4a	284.5b	8.07

[1] Pooled standard error of the mean (n=8)

[2] Within row, means with same letter were not different (P>0.05); letters with an asterisk were not different (P>0.10).

5.4.2 Late spring study

5.4.2.1 Rainfall in late spring

Rainfall at the Pohangina sites was 41 mm and 87.8 mm for November and December 1997. Rainfall at the Rongoiti site was not available and the rainfall record of 40 mm and 50 mm for the region was considered representative for these months (Met Service 1997). Rainfall at Ballantrae was 60.5 mm and 148 mm for the same months. Although the season was under the influence of 'El Niño' weather, the Ballantrae site experienced a benign rainfall pattern when compared with the Pohangina and Rongoiti sites.

5.4.2.2 Soil temperature in late spring

The consistently lower ($P<0.05$) soil temperatures at 0-100 mm depth from the PP area (Table 5.13) reflected the higher θ status and shade in the PP area. Soil temperature was lower while the absolute temperature difference between the vegetation areas increased in December in comparison to November, particularly in the sites with older trees. The Rongoiti site sustained differences of 3.6 and 3.2 °C and also was the site with the largest difference in θ (12.2 %v/v in 0-150 mm) between the vegetation areas (Table 5.14). The weak difference in θ at the 150-300 mm soil stratum in December at the Rongoiti site suggested that the effect of radiation, when modified by shade, influence conditions mostly in the superficial stratum.

Table 5.13. Soil temperature at 100 mm depth in the open pasture (OP) and poplar-pasture (PP) areas at different sites from the South of the North Island.

		November			December			January		
		OP	PP	SEM[1]	OP	PP	SEM	OP	PP	SEM
Site						°C				
Ballantrae		13.8a[2]	13.4a	0.14	16.3a	15.0b	0.21	16.8a	15.6b	0.19
Pohangina	Hill 1	15.0a	13.7b	0.15	18.5a	15.0b	0.21	18.0a	16.1b	0.41
Pohangina	Hill 2	16.1a*	15.3a*	0.27	18.7a	14.7b	0.32	18.4a	16.1b	0.25
Rongoiti		13.1a	9.5b	0.18	15.9a	12.7b	0.27	19.6a	14.4b	0.51

[1] Pooled standard error of the mean.

[2] Within column, means with the same letter were not different ($P>0.05$); letters with an asterisk (*) indicate a $P<0.1$ difference.

5.4.2.3 Soil water in late spring

With the exception of Ballantrae, December θ measurements had lower means than in November (Table 5.14). θ in the PP was similar or higher in November, and definitely higher than the OP area in December. The magnitude of the difference in θ between the OP and PP vegetation areas was

Table 5.14. Soil water (θ) in the OP and PP vegetation areas at 0-300, 0-150, 150-300 mm soil strata in different sites from the south of the North Island.

	Pohangina							
	Hill 1		Hill 2		Rongoiti		Ballantrae	
	Nov	Dec	Nov	Dec	Nov	Dec	Nov	Dec
	θ %v/v							
0-150 mm								
OP	29.5a[1]	23.7a	39.3a*	25.5a	39.9a	26.0a	28.3a	34.1a
PP	30.7a	30.8b	35.0a*	29.7b	54.1b	38.2b	29.9b	36.0a
SEM[2]	0.8	1.1	1.5	0.7	0.7	1.1	0.5	1.0
150-300 mm								
OP	20.9a	26.2a	21.7a	24.6a	21.8a	25.1a*	27.6a	27.6a
PP	25.2b	23.6b	29.9a	25.0a	37.4b	28.8a*	31.3b	32.7b
SEM	0.9	0.6	2.0	1.6	2.3	1.5	0.7	1.1
0-300 mm								
OP	38.2a	24.9a	30.5a	25.0a	30.8a	26.0a	27.9a	30.8a
PP	36.2a	27.2b	32.5a	27.4a	45.8b	33.5b	30.6b	34.4b
SEM	1.1	0.5	0.9	1.0	1.3	1.0	0.5	0.9

[1] Within column, means with the same letter were not different ($P>0.05$); letters with an asterisk (*) indicate a $P<0.07$ difference.

[2] Pooled standard error of the mean.

greater at the 0-150 than at the 150-300 mm stratum and also greater in November. Although the absolute θ varied from site to site and depended on soil type, the desiccating conditions prevailing indicated that θ at the superficial topsoil stratum (0-150 mm) in the PP area was higher. Thus tree shade, decreased θ loss rather than increasing water use at those soil strata.

5.4.2.4 Pasture dry matter accumulation in late spring

PA was consistently lower ($P<0.05$) in the PP areas at sites with mature trees (Table 5.15). For the Rongoiti data, it was necessary to use θ at the 150-300 mm soil stratum as a covariate for error control because some sampling positions were water stressed in the OP area. The average PA in the PP area for sites with mature trees was 40% of the OP area while at Ballantrae it was 94%. There was a tendency to lower PA on the OP area in December in comparison to November. However, PA was not increased in the PP and the OP: PP ratio was maintained despite the higher mean θ at the PP area suggesting, that moisture was not a limiting factor in the PP area. PA was less dependant on θ in the PP with mature trees as suggested by the smaller correlation coefficients ($r < 0.4$) between moisture status and DM accumulation (Table 5.16). As in the *'main study'*, soil temperature also was related with θ at the 0-150 mm soil stratum, with the relation stronger in the PP area of sites with mature trees. At the Ballantrae site, the correlation between moisture status and PA was weak and comparable for the OP and PP vegetation areas, suggesting that the tree effect had a smaller magnitude. The correlation between PA, soil θ and temperature were also weak because climatic conditions remained fairly constant and favourable for pasture growth whereas at the other sites, PA decreased with higher soil temperatures as indicated by their negative correlation due to drier weather.

Table 5.15. Pasture DM accumulation rate in open pasture (OP) and poplar-pasture (PP) areas in different sites from the south of the North Island.

	Pohangina			
	Hill 1	Hill 2	Rongoiti	Ballantrae
November 1997	kg DM ha^{-1} d^{-1}			
OP	60.5a[1]	58.5a	104.1a	52.6a
PP	31.5b	17.1b	35.0b	48.1a
SEM[2]	5.3	4.5	15.6	6.1
ratio OP:PP	0.52	0.29	0.34	0.91
December 1997	kg DM ha^{-1} d^{-1}			
OP	49.7a	53.0a	63.0a*	56.9a
PP	24.8b	18.6b	24.0a*	54.5a
SEM	3.3	3.8	8.3	4.7
ratio OP:PP	0.50	0.35	0.38	0.96

[1] Within column, means with the same letter were not different ($P>0.05$); letters with an asterisk (*) indicate a $P<0.05$ difference using θ as a covariate.

[2] Pooled standard error of the mean.

Table 5.16. Correlation between soil (θ), soil temperature at 100 mm depth and pasture DM accumulation (PA) rate of hill pasture in open pasture (OP) and poplar-pasture (PP) areas in different sites from the south of the North Island.

		θ % v/v			
	Soil stratum	0-150 mm	150-300 mm	0-300 mm	PA rate
		sites with mature trees			
OP	pasture accumulation	0.40	0.19	0.46	
	soil temperature	-0.67	0.22	-0.37	-0.52
PP	pasture accumulation	0.32	0.21	0.32	
	soil temperature	-0.87	-0.51	-0.82	-0.48
		Ballantrae site			
OP	pasture accumulation	-0.14	0.06	-0.06	
	soil temperature	0.44	0.12	0.39	0.04
PP	pasture accumulation	0.13	-0.18	-0.04	
	soil temperature	0.57	0.26	0.50	0.16

5.4.2.5 Pasture botanical composition in late spring

Pasture botanical composition showed a different pattern at the sites with mature poplars than at the younger Ballantrae site, so it is described separately. At the sites with mature trees, grass, followed by legumes were the main botanical components (Table 5.17). Dead pasture material was <11% at both vegetation areas in these sites and tended to be lower in the PP areas. The tree debris component described in the *'main study'* was not present in the spring samples. Although grass was the most abundant component in the plant community, the actual proportion of grass species and ratio to the legume component varied from site to site (Table 5.17). Only differences of large magnitude were detected between the OP and PP areas among the most abundant components because the standard error of the mean was high. Thus, differences significant at α=0.10 also were considered to elucidate the prevailing trends.

The plant community in the OP area was represented, in descending order of occurrence, by *L. perenne*, *C. cristatus*, *A. capillaris* and *T. repens* while in the PP area *Poa spp.*, *L. perenne*, *A. capillaris*, *A odoratum* and *T. repens* were predominant. At this sampling time, only trace numbers of shade tolerant plants such as *D. glomerata* or *Lotus spp.* were found in the PP area and those occur-

Table 5.17. Botanical components as percent of pasture DM at the open pasture (OP) and poplar-pasture (PP) areas at four sites in the south of the North Island in spring 1997.

	L. perenne	*A. capillaris*	*A. odoratum*	*C. cristatus*	*Poa spp.*	*T. repens*	Dead material	Other low fertility grass[1]	Other low fertility legumes[2]	Other species	Grass: Legume ratio
	Percent of DM										
Pohangina Hill 1											
OP	36.4a[3]*	10.1a	7.8a	7.6a	6.6a	14.8a	7.0a*	2.4a	2.9a	4.4a*	0.25
PP	18.5a*	15.3a	12.5a	6.2a	2.5b	11.9a	2.6a*	14.3b	6.8a	9.4a*	0.27
SEM[4]	5.7	3.3	4.4	3.6	1.0	3.0	1.5	2.3	3.9	1.6	
Pohangina Hill 2											
OP	14.1a	14.4a	5.4a	21.1a	1.2a	20.0a	10.5a*	1.2a*	8.6a	3.5a*	0.50
PP	15.2a	17.8a	8.8a	2.0b	20.0b	13.7a	5.3a*	16.2a*	0.0a	1.1a*	0.17
SEM	5.1	4.3	3.1	3.9	2.5	3.7	1.9	4.7	3.7	0.9	
Rongoiti											
OP	37.1a	8.4a	7.1a	12.8a	10.1a	6.4a*	2.7a	0.9a	3.3a	11.3a	0.13
PP	20.9b	4.5a	0.5b	7.2a	38.1b	12.7a*	1.8a	10.2b	0.0a	4.0a	0.16
SEM	4.8	1.8	1.7	3.4	5.5	2.3	1.0	1.6	2.1	3.0	
Ballantrae											
OP	8.2a*	15.4a	24.4a	10.8a	0.3a	7.9a	15.7a	5.1a*	4.1a	8.1a	0.19
PP	23.1a*	5.2b	8.4b	2.9b	8.0b	13.3a	17.8a	18.3a*	0.2a	2.7a	0.20
SEM	3.4	1.7	2.4	1.4	1.3	2.3	1.2	2.7	1.3	1.5	

[1] Grouped *Dactylis glomerata*, *Festuca rubra*, *Holcus lanatus* and *Poa pratensis*.

[2] Grouped *Trifolium dubium*, *Trifolium subterraneum* and *Lotus* spp.

[3] Within column, within site, means with the same letter were not different (P>0.05); letters with an asterisk (*) indicate a P<0.1 difference.

[4] Pooled standard error of the mean.

ring were accounted in the 'other low fertility' (grass or legume) classification (Table 5.17). Although the *L. perenne* proportion was lower in the PP area, it was 15-20 % of the plant community. With the exception of the Rongoiti site, *T. repens* also tended to be slightly lower in the PP area and was 12-14% of the plant community. *Poa spp.* (*P. annua, trivialis* and *pratensis* combined) were consistently higher ($P<0.05$) in the PP than in the OP area, and were the dominant grasses in the PP area of Pohangina Hill 2 and Rongoiti sites.

In contrast with the sites with mature trees, the Ballantrae site showed higher dead pasture material, but the OP and PP areas were not significantly different ($P>0.05$). The OP and PP areas in the Ballantrae site were different in the proportion of low fertility species. *A. capillaris*, *A odoratum* and *C. cristatus* proportions were higher ($P<0.05$) in the OP area while *Poa spp.* were higher in the PP area. Although only significant at the α=0.10 level, *L. perenne* tended to be higher in the PP area. At this site no relationship between botanical components and soil temperature was found and only the 'other low fertility' legumes component was correlated (r= -0.72, $P<0.01$) with θ in the 150-300 mm soil stratum in the OP area.

Table 5.18. Botanical components of pasture on an area basis at the open pasture (OP) and poplar-pasture (PP) areas at four sites in the south of the North Island in spring 1997.

	L. perenne	*A. capillaris*	*A. odoratum*	*C. cristatus*	*Poa spp.*	*T. repens*	Dead material	Other low fertility grass[1]	Other low fertility legumes[2]	Other species
	kg DM ha^{-1}									
Pohangina Hill 1										
OP	641a	173a	139a	134a	114a	264a	116a	44a	51a	77a
PP	187b	141a	105a	81a	19b	125a	26b	113a	33a	81a
SEM[4]	100	52	40	59	14	62	22	28	24	21
Pohangina Hill 2										
OP	225a	263a	89a	383a	18a	324a	167a	20a	141a	64a
PP3	73a	93a	46a	9b	96b	70b	26b	78a	0a	5b
SEM	62	77	25	92	16	52	20	25	62	17
Rongoiti										
OP	1261a	255a	192a	391a*	417a	172a	56a	17a	50a	239a
PP	193b	45b	5b	69a*	404a	132a	20a	113b	0a	35b
SEM	281	51	36	113	178	42	15	22	28	38
Ballantrae										
OP	121a*	257a	390a	166a	2a*	150a	258a	85a	75a	142a
PP	382a*	82b	142b	44b	139a*	205a	274a	268a	4a	39a
SEM	66	33	47	21	29	45	31	41	22	25

[1] Grouped *Dactylis glomerata*, *Festuca rubra*, *Holcus lanatus* and *Poa pratensis*.

[2] Grouped *Trifolium dubium*, *Trifolium subterraneum* and *Lotus spp.*

[3] Within column, within site, means with the same letter were not different ($P>0.05$); letters with an asterisk (*) indicate a $P<0.1$ difference.

[4] Pooled standard error of the mean.

With the exception of Ballantrae, the conversion of botanical components into an area basis showed that *L. perenne*, *T. repens*, *A. capillaris*, *A. odoratum*, *C. cristatus* and dead material presented lower absolute yields in the PP area (Table 5.18), although not always significantly lower ($P<0.05$). The other species that were grouped in *Poa spp* and 'other low fertility' grasses or legumes, generally were similar between the OP and PP areas in the sites with mature trees, but the standard errors were high with respect to the mean. At Ballantrae, *L. perenne* and *T. repens* yield was not different between the OP and PP areas, but showed higher absolute numbers in the PP area (Table 5.18). *A. capillaris*, *A. odoratum* and *C. cristatus* were lower ($P<0.05$) in the PP area while the rest of the botanical components were similar ($P>0.05$) between the OP and PP areas.

5.4.2.6 Pasture botanical composition relations in late spring

For some of the dominant grasses there was a relationship with soil temperature at 100 mm. In the Pohangina Hill 1 a relationship was found between soil temperature in the OP area and the proportion of *A. capillaris* ($r= 0.98$, $P<0.003$) and *C. cristatus* ($r=0.85$, $P<0.06$). In the PP area of the same site, *L. perenne* also was correlated ($r= 0.96$, $P<0.008$) with soil temperature. Similarly in the Rongoiti site, *Poa spp.* were correlated with soil temperature in the OP ($r= -0.83$, $P<0.07$) and PP ($r= -0.97$, $P<0.006$) areas.

Some relationships were also found between components of the plant community and θ in different soil strata. *A. capillaris* was correlated with θ in the 0-150 mm stratum of the OP area in the Rongoiti ($r= 0.96$, $P<0.007$) and Pohangina Hill 2 ($r= 0.94$, $P<0.01$) and in the PP area in the Rongoiti ($r= -0.97$, $P<0.003$). 'Other low fertility' legumes in the OP ($r= -0.86$, $P<0.05$) and *T. repens* in the PP area ($r= -0.98$, $P<0.02$) in Pohangina Hill 1 were correlated with θ in the same soil stratum. 'Other low fertility' legumes in Pohangina Hill 1 ($r= -0.97$, $P<0.003$) and *T. repens* in Pohangina Hill 2 ($r= -0.94$, $P<0.01$) in the PP also were correlated with θ but in the 150-300 mm soil stratum. Similarly, *Poa spp.* ($r=-0.88$, $P<0.04$) and *C. cristatus* (-0.92, $P<0.02$) in Rongoiti and 'other low fertility' grass in Pohangina Hill 1 ($r=-0.90$, $P<0.04$) were correlated with θ in the 150-300 mm soil stratum in the PP area.

5.4.2.7 Pasture feed quality and relations in late spring

With the exception of lipid content at Pohangina Hill 1 and SSS, IVD and ME at Pohangina Hill 2, pasture feed quality indicators were not different ($P>0.05$) between the OP and PP areas (Table 5.19). At Pohangina Hill 1 SSS, ME, IVD and ADF were different at the 0.1 α level between the vegetation areas. Also, the SSS content was different ($P<0.1$) for the OP and PP areas at the Ballantrae site. The Pohangina Hill 1 indicators were in accordance with those obtained in November 1996 in the same site. However, ME, IVD and SSS were slightly higher and CP and lipid content lower in November 1996 in both areas, probably because the December 1997 sampling was a month later into the growing season.

Table 5.19. Pasture feed quality in open pasture (OP) and poplar-pasture (PP) areas in different sites from the south of the North Island.

	CP	Lipid	ADF	NDF	SSS	Ash	IVD	ME
				Percent of DM				MJ kg DM
Pohangina Hill 1					November 1996			
OP	13.8a[1]	3.5a	29.4a	47.9a	10.1a	nm	71.0a	11.2a
PP	15.4b	3.3a	29.1a	48.7a	7.3b	nm	71.2a	11.2a
SEM[2]	0.8	0.1	2.9	3.4	0.4		2.6	0.4
					December 1997			
OP	19.0a	4.4a	28.7a*	45.4a	5.9a*	11.7a	69.8a*	10.4a*
PP	18.9a	4.0b	31.4a*	49.7a	4.8a*	11.5a	65.4a*	9.8a*
SEM	1.6	0.1	0.6	1.6	0.2	0.3	1.0	0.1
Pohangina Hill 2								
OP	16.3a	4.0a	28.7a	47.3a	9.8a	10.6a	71.0a	10.6a
PP	15.6a	4.2a	31.6a	54.0a	4.9b	11.2b	61.3b	9.2b
SEM	1.3	0.2	1.2	2.4	0.4	0.4	0.4	0.1
Rongoiti								
OP	20.7a	4.7a	28.0a	49.4a	5.9a	11.5a	75.1a	11.2a
PP	20.3a	5.0a	29.3a	50.5a	4.9a	12.6b	73.3a	10.9a
SEM	0.9	0.1	2.4	2.9	0.8	0.1	3.1	0.5
Ballantrae								
OP	16.8a	3.7a	27.9a	47.4a	8.1a*	9.5a	67.5a	10.1a
PP	18.9a	3.8a	28.6a	48.9a	6.7a*	10.4b	66.7a	9.9a
SEM	0.9	0.1	0.9	1.4	0.4	0.2	1.1	0.2

[1] Within site, within column, means with the same letter were not different (P>0.05); letters with an asterisk (*) indicate a P<0.1 difference.

[2] Pooled standard error of the mean.

As expected, feed quality was correlated with some botanical components of the pasture community (P<0.05). This relation was examined pooling the botanical composition of the plant communities (n=10 per site) in the same way as the samples for feed quality were bulked (n=4 per site, Ballantrae n=8). The correlation was calculated for the Ballantrae site and combined data for the sites with mature trees. *A. capillaris* was negatively correlated with IVD (*r*= -0.92) and ME (*r*= -0.92) and *Poa spp.* positively with the lipid content (*r*= 0.92) of pasture in the PP area from sites with mature trees. In PP area of the Ballantrae site, only the 'other low fertility' grass (*r*= -0.99) and 'other species' (*r*= 0.99) components were related with the lipid and CP content, respectively.

With the exception of the Rongoiti site, the calculated ratio of CP: ME (Martin 1998) was higher for the pasture growing under shade. At Pohangina Hill 1 the ratio was 18.3 and 19.3, at Pohangina Hill 2 was 15.4 and 17.0, at Rongoiti was 18.5 and 18.6 and at Ballantrae was 16.6 and 19.1 in the OP and PP areas, respectively. As in the '*main study*' a CP surplus was consistent at all sites in diets calculated from pasture in the PP area (Table 5.8).

5.4.2.8 Pasture mineral content in late spring

With the exception of K at Rongoiti and P and S at the Ballantrae site, pasture mineral content was similar (P>0.05) between the OP and PP areas (Table 5.20). Ballantrae and the sites at Pohangina also showed a tendency for higher K pasture content in the PP area, but the small number of samples and higher standard error precluded the differentiation of the means. With the exception of Pohangina Hill 2 site, the Ca: P ratios were similar (P>0.05) between the OP and PP areas (Table 5.21). With the exception of the Ballantrae site, the K:Na ratio was different in pasture from the OP and PP areas (P<0.05).

Table 5.20. Pasture mineral content in the open pasture (OP) and poplar-pasture (PP) areas in different sites from the south of the North Island.

	Pohangina											
	Hill 1			Hill 2			Rongoiti			Ballantrae		
	OP	PP	SEM[1]	OP	PP	SEM	OP	PP	SEM	OP	PP	SEM
						µg /g						
Al	527.5a[2]	664.0a	73.0	344.0a	812.5a	101.4	370.5a	473.5a	70.6	294.5a	314.7a	50.6
As	1.0a	1.0a	0.0	1.1a	1.0a	0.0	1.0a	1.0a	0.0	1.1a	1.1a	0.0
B	14.0a	12.0a	4.1	14.3a	7.2a	1.6	8.2a	7.7a	0.6	10.1a	9.8a	2.3
Co	0.3a	0.6a	0.2	0.3a	0.3a	0.0	0.3a	0.5a	0.1	0.4a	0.4a	0.0
Cu	8.6a	11.3a	0.8	7.2a	8.4a	0.4	9.8a	11.2a	1.0	7.1a	7.5a	0.9
Fe	436.5a	574.5a	68.0	392.5a	750.0a	103.0	377.5a	508.5a	68.8	318.3a	352.0a	45.2
Mn	262.5a	156.0a	49.8	301.0a	159.0a	32.5	137.5a	64.5a	12.3	402.0a	334.0a	40.6
Mo	0.3a	0.4a	0.1	0.3a	0.3a	0.0	3.1a	5.5b	0.3	0.4a	0.4a	0.0
Ni	2.1a	2.7a	0.3	7.5a	3.5a	1.0	1.9a	5.4a	3.5	2.2a	1.0a	1.2
Pb	3.3a	3.5a	0.1	3.5a	3.5a	0.1	3.5a	3.4a	0.1	3.5a	3.6a	0.1
Se	3.4a	3.5a	0.1	3.5a	3.5a	0.1	3.5a	3.4a	0.1	3.5a	3.6a	0.1
Si	141.0a	177.5a	23.7	146.0a	169.0a	15.7	144.0a	167.5a	15.2	220.5a	167.0a	58.2
Sn	0.7a	0.7a	0.0	0.7a	0.7a	0.0	0.7a	0.7a	0.0	0.7a	0.7a	0.0
Sr	58.4a	65.3a	8.7	57.7a	51.0a	5.8	42.6a	48.7a	3.6	49.2a	47.9a	3.7
						mg/ g						
Ca	6.8a	7.1a	1.1	6.0a	5.1a	0.4	5.2a	5.8a	0.6	5.3a	5.5a	0.5
K	26.5a	27.2a	3.4	17.7a	26.6a	2.9	31.7a	37.6b	0.2	23.7a	28.0a	2.0
Mg	2.6a	2.3a	0.4	2.1a	2.1a	0.2	2.1a	2.1a	0.2	2.0a	2.1a	0.1
Na	2.9a	1.2a	0.5	4.6a	1.3a	0.9	1.6a	0.7a	0.1	1.6a	1.7a	0.3
P	3.5a	3.2a	0.6	2.5a	2.9a	0.3	3.1a	3.6a	0.3	3.1a	3.8b	0.2
S	2.7a	2.5a	0.3	1.9a	2.2a	0.1	2.8a	2.9a	0.2	2.2a	3.0b	0.2

[1] Pooled standard error of the mean.

[2] Within row, within site, means with the same letter were not different (P>0.05).

Table 5.21. Calcium: Phosphorus and Potassium: Sodium ratios in the pasture from open pasture (OP) and poplar-pasture (PP) areas at different sites in spring.

	Ca:P			K:Na		
Pohangina	OP	PP	SEM[1]	OP	PP	SEM
Hill 1	1.9a[2]*	2.2a*	0.01	9.7a*	22.4a*	2.5
Hill 2	2.4a	1.8b	0.01	4.2a	21.3b	1.5
Rongoiti	1.7a	1.6a	0.02	20.3a	54.7b	6.2
Ballantrae	1.7a	1.4a	0.2	15.4a	18.9a	3.2

[1] Pooled standard error of the mean.

[2] Within site, within ratio, means with the same letter were not different (P>0.05); letters with an asterisk (*) indicate a P<0.1 difference.

5.5 Discussion

When comparing the open pasture and the poplar-pasture vegetation areas different measurements indicated that the poplar trees modified the total solar radiation (0.1-4 μm visible, photosynthetically active and heat radiation) transmitted through the canopy. Reduced infrared radiation in the poplar-pasture area influenced the soil temperature-moisture complex, while decreased photosynthetically active radiation (0.4-0.7 μm) modified plant communities and decreased their growth. In addition, the poplar canopy directly decreased available rainfall to the pasture understorey, adding another complexity to soil temperature-moisture relations. The tree effect had a dynamic and rather heterogeneous influence that was measured as the variation in soil water around the trees and demonstrated by images of the projected canopy area. This study showed that understorey pasture accumulation was affected primarily by reduced radiation but also can be reduced by moisture stress (Gilchrist et al. 1993). The resulting light, temperature and moisture effects in the poplar-pasture agroforest could not be evaluated independently in this field study and this is taken into consideration in the following discussion.

5.5.1 Micro climate changes

In the present study pasture under the poplar had lower growth than in the open pasture. Shading by trees was the most evident difference between the vegetation areas examined and had an indirect effect on soil temperature. Changes in soil temperature of the magnitude found in the poplar-pasture area in this experiment have been recorded under full leaf of ash trees (*Fraxinus spp.*) in England (Dupraz & Newman 1997). In temperate climates like in New Zealand, lower soil temperatures under *P. radiata* trees contributed to lower pasture production (Hawke & Wedderburn 1994) at a range of tree stockings. Differences in pasture growth have been observed as a result of sun transit (Dupraz & Newman 1997) and/or the shading pattern around individual trees (Gilchrist et al. 1993). Cast shade reduces soil temperature during summer and this could be beneficial for pasture growth, but in winter the temperature in the present study decreased to 7°C which limits pasture growth. Although the poplar-pasture area would be receiving full sunshine during winter, soil temperatures were so low that probably resident pasture could not grow very much at that time.

It is known that soil properties under individual trees develop distinguishable patterns centered in radial symmetry to the trunk (Zinke 1962). In the present experiment canopy shading was reflected in the amount of soil water under the canopy at various aspects and distance from the tree trunk. Similarly, the soil temperature and hill slope helped to explain the differences in soil water between the two vegetation areas (about 2.5 %v/v). This was attributed to the tree planting being biased towards the more broken and damaged terrain and the cooler conditions under the tree canopy. The differences in soil moisture between the open pasture and the poplar pasture and around the trees had a small magnitude in most of the months sampled. Soil water generally was not limiting but during January 1996 water availability in the topsoil was low. The significance of soil water shortage during summer will depend on the duration of the dry spell and the occurrence of "El Niño". Considering the data from Rongoiti during spring 1997, a dry spell would influence soil water in the open pasture area first and then under the trees.

Soil nutrient fluxes in the poplar-pasture can be modified by canopy shade. Nitrogen fixation, organic matter accretion and oxidation rates are sensitive to temperature and moisture, and canopy shading has an influence on these climatic factors. Soil total nitrogen and plant available phosphorus were lower (300 kg N ha and 5.1 kg P ha), and soil pH and potassium were higher (0.5 pH units and 111 kg K ha) in the PP compared to the OP area (0-75 mm soil strata, see section 4.4.2.2-3). Although total nitrogen appeared to be reasonable for pasture production, the mineralisable fraction was not determined. In the incubation experiment leaf litter added about 93 kg N ha (1.04 % N) to the open pasture topsoil treatment. However, grass yield was very low in the leaf litter amended treatment during the first 4 months (eight cuttings), possibly N was immobilised. Grass yields in the poplar pasture topsoil, were very good during the first two months, and then declined suggesting that N was readily available but was quickly exhausted in the absence of legumes. Because soil media was collected in December, nine months after leaf fall, it was possible that mineralisable N and Olsen P were higher in the poplar-pasture topsoil than in the leaf litter amended open pasture treatment (see section 4.4.1). On the other hand, legume treatments supported higher pasture yield and for longer than grasses. If nitrogen was the only limiting nutrient in the first eight cuttings, then N fixation overcame this shortcoming. Phosphorus and K could be also limiting unless included in the system.

The higher soil pH under the poplars will limit the amount of P mineralisation, but also their retention. Phosphorus animal cycling, fertilisation and leaf litter would be the only sources of P into the system but their contribution needs to be determined. Potassium was abundant in the poplar-pasture topsoil and the amended open pasture treatments in the incubation study and also in the topsoil of the PP area. It is possible that K as well as Ca would not be limiting when seasonal inputs of leaf fall occur. If these relations prevail in the field, then plant available N and P could be enough for pasture growth at some times (summer) but completely unavailable at others (autumn). This effect would be more dramatic in the field because nutrient fertility was not evenly distributed in the 0-300 mm soil stratum to the same extent as in the open pasture. The higher concentration of nutrients in the 0-20 mm soil stratum probably implies nutrient storage by organic matter and not by clays and potentially higher availability to plants or microorganisms when leaf fall occurs.

Soil pH further complicates the understanding and consequences of nutrient fluxes, storage and availability. The poplar-pasture soil pH in the superficial 20 mm soil stratum (5.4, after incubation) appears to be lower than soil pH from the field study (6.0 at 0-75, 5.9 at 75-150 and 6.0 at 150-300 mm). It could be possible that mineralisation rates of P in the 0-20 mm stratum were higher and also N would be very mobile at this pH. However, below 20 mm stratum the lower pH would act as a safety net for NO_3^-.

Soil microclimate in the poplar-pasture is dominated by canopy shading as it influences soil temperature, water and fertility. Pasture also is directly affected by the amount and quality of light filtrated through the canopy. Tree litter overlaying the pasture canopy and its subsequent incorporation and decomposition in the topsoil have the potential to alter pasture growth. If N immobilisation results after leaf fall, then combined with low soil temperatures during winter would result in very small growth of grass, but perhaps not for legumes. The hypothesis of greater growth of legumes during winter is based on the favourable N-fixation, soil water and pH and light conditions. However in June 1996 legumes were only 5% and in May 1997 were 12% of the sward composition under the poplars (Table 5.6). It is very likely that important interactions occur in the microclimate during winter and at other times of the year. Figure 5.9 presents the relative importance of the factors described in relation to their capacity to influence pasture growth during the year.

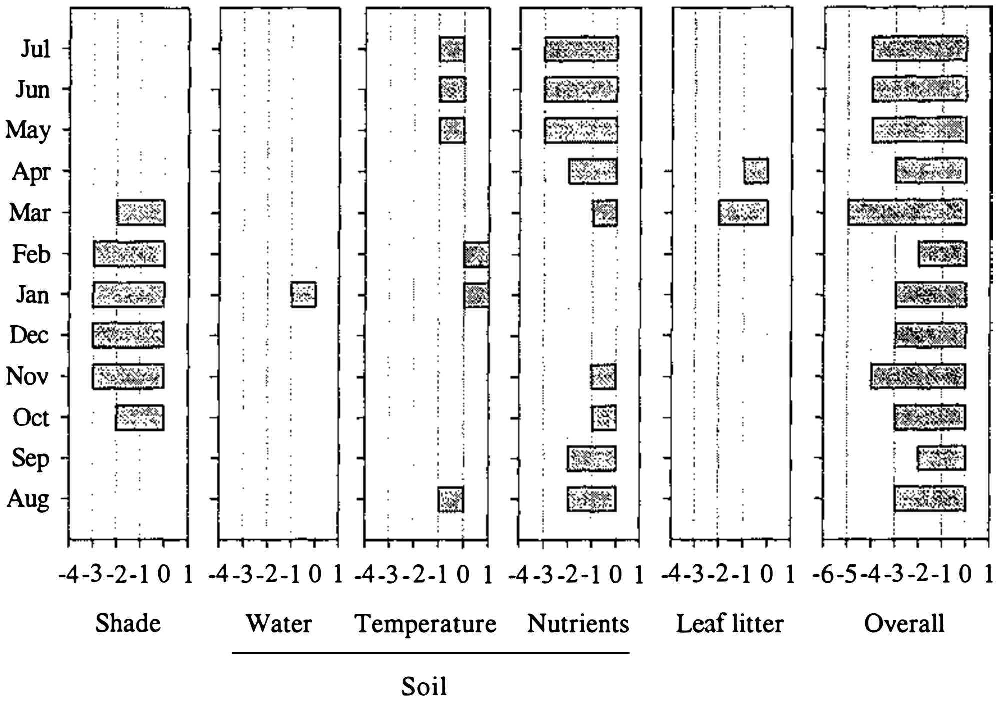


Figure 5.9. Proposed influence of microclimatic factors on pasture production as modified by the tree canopy in poplar-pasture system during the year. Relative weights were given as 0 no influence, 1 minor influence, 2 medium influence and 3 great influence.

5.5.2 The tree canopy

Canopy structure has been related to understorey productivity as a function of tree density and stand age (Sibbald et al. 1994). In a *P. radiata* silvopastoral system, *T. repens* and *L. perenne* dry matter decreased with increasing tree density (range 50, 100, 200 and 400 sph) and stand age mainly as a consequence of light, soil nutrients and water competition (Hawke 1991). Canopy closure, expressed as the ratio of projected tree canopy to ground area covered, has been used to estimate pasture production in *P. radiata* silvopastoral systems by Knowles et al. (1997). Their model predicted 0% pasture production (relative to open pasture production) at around 70% of *P. radiata* canopy closure development ($R^2 = 0.89$). If the poplar and pine canopies were comparable, then the 70% measured canopy closure ratio in the Pohangina Hill 1 poplars should result in pasture accumulation of 11.2% of that of the open pasture, and not the 60% pasture accumulation (6.2 vs. 10.6 t ha^{-1} yr^{-1}) measured directly under the poplars. The discrepancy was attributed to the leaf area index that mature stands of broadleaved (around 6) or coniferous (as high as 15) trees can attain (Ong & Monteith, 1993) and poplars being deciduous. This relation suggested that the *P. deltoides* canopy could transmit more radiation through the canopy than *P. radiata* during the growing season and support higher understorey growth. Apart from the canopy density, transmittance has been reported to vary with leaf optical properties throughout the season and also with specific *Populus* clones (Sattin et al. 1997). The maximum and minimum values of photosynthetically active radiation registered indicated that illumination conditions were quite dynamic under the poplar canopy. Part of the variation could be attributed to sunflecks, which can contribute a substantial fraction of the total light energy available for carbon gain by the understorey (Medina 1986). Thus, the particular canopy arrangement and properties influencing the reflectance (albedo) and porosity of a given species may modify the canopy closure proportion that limits the understorey growth. Although in the present study stand edge effects were avoided, sidelight is another important factor in the space planted poplar-pasture system.

Pinus decrease soil pH at high tree densities (Hawke & O'Connor 1993), while poplars would increase pH (see section 4.4.2.1). Also poplar leaf litter decomposes faster than pine needles (Taylor & Parkinson 1988b). Floor litter also contributes to decreased pasture production under pines (Hawke et al. 1993). However, an important consideration of the model presented by Knowles et al. (1997) is that pasture dry matter production under the trees was assessed on areas free of pruning and thinning debris (Hawke 1991) and the effect of litter on the assessment of pasture production would be minimised.

The present study examined the influence of tree effects directly beneath the tree canopy. However, most of the differences found in relation to the open pasture were likely to decrease in the pasture areas away from the tree crown (Benge 1987). The intensity of the tree effect has been reported to decrease when measurements were made increasingly away from the canopy or tree root domains (Zinke 1962, Gilchrist et al. 1993, Thevathasan & Gordon 1997). Because the poplars of this study were widely spaced, there were gaps of pasture less affected by tree shade. The overall effect of a unit area of the agroforest on pasture accumulation would be the summation of the influence patterns occurring under the shade of trees and the gaps outside these areas (Zinke 1962). The precise dimension of the gaps is dynamic in nature, but depends on the canopy structure of the overstorey. Using the ratio of canopy closure to represent sunflecks getting through the canopy (porosity) and gap areas and assuming:

- that pasture production would be at the most, similar to that in the open;
- that the pasture production during autumn-winter has a different magnitude as a consequence of porosity and gaps;
- that the negative effect of poplar leaf litter on pasture production is also a function of canopy structure;

the understorey pasture accumulation (UPA) in the present poplar agroforest would be 7.52 t ha^{-1} yr^{-1} or 71% of the 10.6 t ha^{-1} yr^{-1} grown in the open pasture:

$$UPA = (PA_p \times CCR) + \lfloor PA_g \times (CCR - 1) \rfloor \qquad (4)$$

where PA_p was pasture accumulation (DM t ha^{-1} yr^{-1}) in the poplar-pasture area, PA_g the pasture accumulation (DM t ha^{-1} yr^{-1}) in the open pasture area and CCR the decimal expression of the canopy closure ratio. The use of CCR instead of the single tree gap area (STGA) used to calculate stand transpiration (see section 3.4.5) accounts for the more dynamic nature of sunlight and sunflecks through the canopy during sun transit and canopy disturbance by wind. On the other hand STGA is a proxy of the tree canopy area in relation to other trees and the porosity (structure) of the canopy is not accounted, this is small gaps within a tree crown are disregarded.

5.5.3 Shade and pasture growth

Competition for light is the primary limitation when water and nutrients are freely available (Ong et al. 1996). Perennial pasture must endure stressful situations that limit the availability of these resources including shading (Sanderson et al. 1997). The effect of shade on perennial pasture includes changes in plant morphology to maximise light interception and physiological processes to enhance the efficiency of C utilisation (Sanderson et al. 1997). Some of the most important responses to shade are increased leaf area and stem elongation (Allard et al. 1991, Devkota et al. 1997), reduced transpiration (Ong et al. 1996), smaller stomata (Wilson & Cooper 1969), and decreased cell wall components (Kephart & Buxton 1993). In general, shade impacts on plant development by reducing the photosynthetic rate (Ong et al. 1996), but actual radiation use efficiency may be increased (Cruz 1997b). Pasture species response to shade should be made considering the different photosynthetic pathways. For instance, C_4 grasses have greater light-saturated photosynthetic rates, and they are prone to reduce assimilation with even minimal shading (Squire 1990). On the other hand, C_3 plants have lower light-saturated photosynthetic rates and a conservative conversion coefficient for water of around 4 kg mm^{-1} kPa^{-1}, compared to 8 kg mm^{-1} kPa^{-1} for C_4 plants (Squire 1990). Thus C_3 plants are most likely to benefit from microclimatic conditions under the tree canopy. The common association of a C_4 understorey in tropical silvopastoral systems suggests that the shading effect will be more dramatic in the tropical than in the temperate counterpart.

The photosynthetically active radiation measured under the poplars was as low as 20% of that in the open pasture. Devkota et al. (1998) evaluated the growth of *L. perenne* and different *D. glomerata* cultivars under the shade of red alder (*Alnus spp.*) trees in New Zealand. Three pruning regimes gave the levels of shade of 17% (759 μmol m^{-2} s^{-1}), 27% (262 μmol m^{-2} s^{-1}) and 77% (166 μmol m^{-2} s^{-1}) of PAR in the open pasture. Shade negatively affected tillering, leaf area and leaf dry weight more in the *L. perenne* than all the *D. glomerata* cultivars, especially at the 77% shade level. Under open pasture conditions, shaded tillers produce a succession of leaves with progressively smaller capacity to use bright light when they eventually emerge into it (Woledge & Parsons 1986). In another experiment, Devkota et al. (1997) used shade cloth and glasshouse conditions and determined that *L. perenne* and *A. capillaris* decreased shoot dry weight at a similar rate with increasing shading, but at a higher rate than that of *T. repens*. If these pastures species behaved similarly under the poplar shade, the work of Devkota et al. (1998) explained in part, the results obtained under the poplar canopies in the present study. Because light in the PP area was reduced to 20% of that in the OP it constrained pasture growth and imposed morphogenic processes like shoot elongation and etiolation.

5.5.3.1 Shade and *Trifolium repens*

In the present study, legume content was typical of New Zealand hill country pastures (Lancashire, 1990) but showed seasonal variation in pasture dry matter. *T. repens* was the predominant legume in the plant community and its proportion was similar between the poplar-pasture and open pasture areas in December 1997. At other sampling times, *T. repens* was the main legume, but its proportion within the legume species was not determined. Examination of actual *T. repens* yield in December 1997, showed that this species was lower in the poplar-pasture area, particularly in the sites with mature trees. Botanical composition in the open pasture in the Ballantrae site was in agreement with the determinations of Saggar et al. (1997) in plots of similar soil fertility. Lower *T. repens* was expected in the poplar-pasture areas with mature trees, since *T. repens* not only has lower photosynthesis in shade, but decreased photosynthetic potential as well (Woledge & Parsons 1986). However, the photosynthetic potential of *T. repens* may not be affected by shade conditions within the sward, unlike laminae of grasses. The main mechanism involved is the extension of petioles before the leaflets are fully open thus, ensuring that the laminae are at the surface of the canopy (Dennis & Woledge 1983). However, this varies between cultivars (Frame et al. 1998). It was possible that *T. repens* was better equipped to survive than grasses under the shade of poplars and in this way, was able to be an important component in the plant community.

Shade also influences *T. repens* growth by reducing N-fixation (Hartwig & Nösberger, 1994). Goh et al. (1996) indicated that legumes fixed more N away from young *P. radiata* trees and suggested that the effect should increase with the age of the trees. Although the yield of *T. repens* in the poplar-pasture area was only 47% of the yield in the open pasture in the Pohangina Hill1 site, the topsoil total N pool (0-75 mm soil depth) in the poplar-pasture area measured in June 1997 was 90% of that in the open (see section 4.5.2.2). Probably the *T. repens* population added N at a lower rate to the poplar-pasture system over the years, but also the system had lower N requirements for pasture production when compared to the open pasture, particularly in the later years. Also, tree demand is lower due to nutrient retranslocation. Also, it was possible that leaching losses were smaller since the trees could act as a safety net and capture the N resource into the system once again (van Noordwijk & Purnomosidhi 1995). Parfitt et al. (1997) measured reduced leaching from the soil of a *P. radiata* forest soil in comparison with the open pasture, mainly because the soil of the later exceeded field capacity earlier in the season and remained wetter later into the summer.

The legume relations found in the present study are particularly important since N-fixation by legumes, i.e. *T. repens*, has been instrumental in the consolidation of forage-legume use in New Zealand pastures, and because there are growing concerns about N leaching from pastoral systems (Frame et al. 1998).

5.5.3.2 Shade and *Lolium perenne*

When the grass proportion by species was partitioned in December 1997, *L. perenne* was one of the dominant grass species of the plant community in the poplar-pasture areas. As with *T. repens*, actual yield of *L. perenne* was expected to be lower in the poplar-pasture area since it is not a shade tolerant species (Devkota et al. 1998). Nevertheless, it has been demonstrated that *L. perenne* had superior shoot yield to *D. glomerata* (a shade tolerant species) when grown under moderate shade in the range of 262-759 μmol m^{-2} s^{-1} (Devkota et al. 1997, 1998). However, decreased survival resulted from reduced tillering ability (Ong & Marshall 1979, Devkota et al. 1997) of *L. perenne* and did not perform well when severely shaded. There is evidence that *L. perenne* is more susceptible to shorter defoliation intervals than *D. glomerata* (Naba Devkota personal communication) under shade, compared to the open pasture. Therefore, survival of ryegrass in silvopastoral systems will be dependent more on grazing management.

5.5.3.3 Shade and dominant species

The dominance of *L. perenne* and *T. repens* in the plant community during December 1997 was attributed to the seasonal growth patterns of each of the individual species. Lambert et al. (1986) found that *Poa* species and ryegrass have maximum growth rates in spring while most low fertility adapted grass produce maximum growth in late spring to early summer. Suckling (1960) characterised the seasonal production of pasture in the hill country of New Zealand and found that *L. perenne* and *T. repens* were at their highest DM production in December-January while the peak DM production for *A. capillaris*, *A. odoratum*, *C. cristatus* was in September-November. In the present study it was observed that these grasses achieved relatively advanced flowering stages in comparison to *T. repens* or *L. perenne* at the time of sampling. Nevertheless, other factors might have contributed to the differences in botanical components. Dry weather originated higher soil temperature and lower soil water in the open pasture areas, probably constraining legume development and triggering early maturing of grass species.

In the present study, it was assumed that the grass and legume species growing in the open pasture and the poplar-pasture areas of each site had the same genotype. However, it is known that *L. perenne* and *T. repens* can evolve as differentiated ecotypes of the species in response to natural selection (Caradus & Snaydon 1988, Snaydon & Davies 1982). For example, Thompson (1993) isolated two genotypes of *T. repens* that had different responses to shade levels. The genotype collected under the *Fraxinus excelsior* canopy maintained better growth (e.g. petiole and internode elongation) than the open pasture genotype in deepest shade (35% PAR from open pasture). These results suggest that the occurrence of different ecotypes in the open pasture and poplar-pasture could not be discounted.

Pasture accumulation was reduced in the poplar-pasture system, but the trees did not have a great influence on the proportion of species in the sward community in spring. This suggested that *L. perenne* and *T. repens* were able to respond to the seasonal changes under the poplar canopy and return in spring to a comparable level to that of the open pasture. Probably the late-autumn period resets the morphological changes (including tillering ability) forced by the shady environment from mid spring to summer. If this is the case, *L. perenne* and *T. repens* could be able to rapidly colonise the smothered landscape (by shade and leaf fall) during late autumn and winter. Although in the present study the population dynamics of these species were not followed, the pattern throughout the growing season of the legume component suggests that *T. repens* and possibly *Lotus spp.*, have a more opportunistic growth than in the open pasture given the changing illumination. Because shade tolerant species were not predominant in the poplar-pasture sward community, the response to shade was an overall reduction in pasture accumulation. On the other hand, the higher contribution in seed bank and tillers of low fertility grass species (*A. capillaris* or *T. repens* for example) probably facilitated their dominance although the tillering ability or grow rates are smaller than those of shade tolerant species.

5.5.4 Soil water

Differences in soil water between the open pasture and poplar-pasture areas were restricted to some autumn and winter months. This was probably a lag consequence of water use by the trees and pasture during the more demanding summer period. This was reflected in the sharp soil water decrease from November 1996 to January 1997 in the poplar-pasture area. Even if the topsoil in the poplar pasture area have had a similar volumetric moisture level than the open-pasture, the stonier profile in open-pasture should have a higher water potential, close to saturation, more often during the year. Rainfall interception in the poplar-pasture could contribute to lower recharge in the topsoil under the trees. Although the topsoil from the open pasture and poplar-pasture may have a distinct recharge pattern, it was not likely to affect pasture growth in this temperate climate. On the other hand, work in a semi-dry mediterranean climate with a *P. pinaster* agroforest indicated that soil water and not light was the limiting factor for pasture growth (Braziotis & Papanastasis 1995). Also, Goh et al. (1996) attributed lower N fixation by legumes in the sunny aspect of young *P. radiata* agroforest rows to moisture stress. However, Huber & López (1993) reported that the superficial stratum in open pasture occasionally reached wilting point during summer, but that was not the case in a nearby *P. radiata* agroforest (733 sph) due to deeper water extraction.

Change in soil water was measured only for two days every month. However, the values obtained gave a crude representation of soil water dynamics throughout the year in the Pohangina Hill 1 site. The generally smaller change in soil water in the 150-300 mm soil stratum in the poplar-pasture area was of particular interest because it indicated that soil water was more constant during the growing season of poplar. Extrapolation of the water balance model obtained in November 1996 to the following months was not accurate because it yielded lower than expected evapotranspiration estimates for the poplar understorey. A possible explanation is that the poplar canopy was at different stages of development in November when the throughfall model was obtained and December when extrapolation was intended. Also, understorey or tree water could be higher in December. In any case, topsoil water and the change in topsoil water suggested that the water reserve was able to cope with the increases in evapotranspiration late in spring and summer in the poplar understorey.

The similar soil water in the open pasture and poplar-pasture areas was determined by distinct mechanisms identified in the rainfall partitioning study (see section 3.6). The tree canopy, by means of rainfall interception and shading the understorey, decreased water losses by evapotranspiration in the topsoil. Higher photosynthetic rates have been associated with increased canopy conductance (Jarvis & Davies 1998). Probably the opposite occurred with the pasture understorey and water use decreased for this vegetation component. In part, this was confirmed by the smaller daily change in topsoil water in the poplar-pasture area, particularly in the 150-300 mm soil stratum. This evidence supported the hypothesis that evapotranspiration was governed by the available radiation under the tree canopy (McNaughton & Jarvis 1983).

Soil water in the 0-150 mm soil stratum was higher than in the 150-300 mm because water did not move uniformly in the 0-300 mm soil stratum. The PP 0-150 mm soil stratum had a higher organic matter and water holding capacity than the lower stratum. This represented a boundary and the large, rapidly transmitting pores of the sandy loam at the 150-300 mm remained empty until the water potential in the 0-150 mm increased to a level which enabled these large pores to fill. A similar effect occurred at the boundary between the OP 0-150 mm and the gravely 150-300 mm soil strata. Organic C was only measured at 0-75 mm soil profile but organic S was determined at various strata and therefore, is used here as an indicator of organic matter distribution in the soil (see sections 4.4.1 and 4.4.2.3). Organic sulphur was higher (18 mg/kg) in the PP 0-20 mm stratum than the OP 0-20, 75-150 and 150-300 mm strata (7, 7, 3 and 4 mg/kg, respectively) and the PP 0-75, 75-150 and 150-300 mm strata (7, 4 and 5 mg/kg, respectively). The higher organic matter in the 0-150 mm of both, the OP and PP probably determined the most important plant available water pool in these sandy soils and water movement between the 0-150 and the 150-300 mm strata.

5.5.4.1 Soil water and pasture species

Moisture stress has been identified as an important factor limiting *T. repens* in a range of conditions (Hutchinson et al. 1995). This was the case in January 1996 at Pohangina Hill 1 and with the exception of the Ballantrae site, in December 1997. The susceptibility of *T. repens* to moisture stress even when shaded by trees, was supported by the negative correlation found in December 1997 between the legume botanical components and soil water in the poplar-pasture area, which indicated that the drier sampling positions had lower legume content. In the open pasture area, such relationship was not significant, possibly because iradiation was more uniform than under the patchy shade of the poplar canopy. With the exception of the March 1997 sampling, botanical components of the plant community suggested that legumes were able to develop adequately in the poplar-pasture area assuming that shade had a comparable effect on all botanical components. *T. repens* could also benefit from favourable soil water, alleviating stress for longer from the onset of a dry spell, as the data from Rongoiti suggested. In general, moisture relations indicated that tree shade should have a more positive influence on understorey productivity when water is more limiting (Belisky et al. 1993). However, work in Germany has shown that water available to grass was reduced to about 50% by 30 year old poplars planted at 96 sph and also the PAR light reaching the *L. perenne* understorey was reduced by more than 50% (von Boberfeld 1986). Braziotis & Papanastasis (1995) also indicated that soil water might become a limiting factor in understorey herbage yield in pine silvopastoral systems developed in semi-dry Mediterranean areas. Gilchrist et al. (1993) expressed a similar opinion about moisture competition when obtaining decreased pasture yield under poplars in the East Coast of the North Island of New Zealand, which is an area more susceptible to dry summers than the sites reported here.

5.5.4.2 Soil water and poplar leaf litter

The leaf litter layer also possibly explained a different wetting pattern in the poplar-pasture area during the autumn months. It is known that aspen leaves (*P. tremuloides*) absorb water readily and saturate completely after 24 h (Taylor & Parkinson 1988c). Thus, the holding capacity of leaf litter (Helvey & Patric 1965) could intercept and store rainfall to be later evaporated (Meentemeyer 1978) or infiltrated into the soil. In the present study, this effect may have contributed to the soil water decline in the poplar-pasture area in March 1997 and to the steady increase of soil water at the 0-150 mm stratum thereafter until June 1997. Leaf litter interception was reported to be as high as 8.9% of annual rainfall in a native evergreen forest in Chile (Huber Oyarzún 1992). Consistent, but lower values (2-5% of annual rainfall) have been measured for deciduous broadleaved forests in North America (Helvey & Patric 1965).

5.5.5 Shade and feed quality

The absence of a shade effect on protein, NDF content and *in vitro* digestibility of the mixed pasture initially suggested that shade was not a dominant factor in determining feed quality. On closer examination, rather than a direct effect on protein nutrition, shaded pasture altered the nutritional balance and may have indirect consequences in animal production. SSS were found to be lower in the pasture understorey and they accounted for the reduced ME content because NDF and ADF fractions were rather similar between the open pasture and poplar-pasture forages. In addition, it was found a low Na and high K relationship in the pasture understorey that could influence Na nutrition and forage palatability. Previous reports, using single species swards or under stressed environments that claimed improved forage quality might not be completely applicable to the conditions of the present work. The contributions of the major nutrient fractions probably involved in a nutritional imbalance are discussed in the following sections.

5.5.5.1 Protein

With the exception of Pohangina Hill 1 site in November 1996, the pasture crude protein content of the poplar-pasture area was similar to or lower than that in the open pasture. These results did not agree with previous reports. Kephart & Buxton (1993) indicated that stressful growth conditions such as shade that limit photosynthate, might improve forage quality of C_3 and C_4 grasses by increasing N content, lowering cell wall concentration and causing small increases of *in vitro* digestibility. These authors worked with artificial shade levels of 690 and 1424 μmol m^{-2} s^{-1} (0.4-0.7 μm) for the average midday PAR in cloudless days. Similar responses to shade have been reported by Deinum et al. (1968) when reducing light intensity to 30% from that in the open pasture.

Higher N content of pasture in tropical silvopastoral systems has been related to increased soil N mineralisation under shade when N mineralisation is limited in the open pasture due to low soil water (Belisky et al. 1993, Wild et al. 1993, Wilson & Wild 1995). Factors such as soil water and earthworm populations have been associated with increased N mineralisation (Wild et al. 1993). Nevertheless, work in New Zealand does not support the findings from tropical environments. The N content of the green pasture component declined with a *P. radiata* stocking of 100 sph and higher (Hawke et al. 1993). Also, a decline in earthworm population has been associated with increasing tree stocking and a decline in pasture growth under *P. radiata* (Yeates 1988, Yeates & Boag 1995). In the present experiment, earthworm numbers were lower for the poplar-pasture while earthworm mass was lower or similar in comparison to the open pasture (see section 4.4.2.5).

Several factors may contribute to the lower total N pool in the poplar-pasture compared to open pasture areas and the lack of shade effect on total N in the topsoil. Most of the time, dead pasture material with high C:N ratios did not accumulate in the system because the objective of the grazing system used was precisely to avoid that. Pasture litter disappearance in New Zealand pastures has been estimated to peak in winter (5%) and is lower in mid summer at about 2% (Zyskowski et al. 1997). In the present experiment, soil water in the open pasture area was limiting only during summer and most of the pasture dead material disappeared during the winter as proved by the botanical composition data. In fact, the poplar-pasture system received a large input of tree leaf litter in autumn that might be seasonally affecting the total N pool size. Studies of deciduous hardwood forests have shown that during a 1-month period in the autumn, there is a peak of carbon input into the forest that is equivalent to >80% of the annual above-ground and 20% of the below-ground input (Hendrick and Pregitzer, 1993). Also, lower soil temperatures under shade appear unlikely to benefit litter breakdown, and actually, should slow it in relation to open pasture. In the long term, the magnitude of the soil total N pool was likely to be self-regulated by legume N-fixation or nutritionally constrained (Whitehead 1995). However, the important *T. repens* component found in the poplar-pasture area (> 11% DM) in December 1997, suggested that some environmental factors must have been favourable to this species in the poplar-pasture area. Soil acidity has a major effect on the rhizobium-*T. repens* symbiosis. *Rhizobium leguminosarum* bv. *trifolii* grows better at pH 5.0 or above and benefits from higher Ca concentrations (Frame et al. 1998). Probably *T. repens* benefited from the higher pH and Ca levels found in the poplar-pasture area (see section 4.5.2.1) and higher plant available P in the top 20 mm (see section 4.4.1). Grazing management could also be beneficial to *T. repens*, close grazing will increase the red:far-red ratio at the grass canopy level. Low red:far red ratios have also been associated with decreased *T. repens* plantlet production (Teuber & Laidlaw, 1996).

5.5.5.2 Soluble sugars and starch

Chemical composition of the poplar-pasture understorey could be influenced by morphogenic and physiological changes brought about by overstorey shading (Huxley 1996). Wong & Stür (1994) determined that reserves of total nonstructural carbohydrates (TNC) stored in the stubble of tropical grasses decreased with frequent defoliation under artificial shade, and this was an important adaptive feature for growth and persistence under shade. Leaf starch concentration was also reduced in *Salix aquatica* (Waring et al. 1985) and *Cynodon dactylon* (Burton et al. 1959) when grown in shade. Similar decreases in shoot (Alberda 1965, Deinum et al. 1968) and root (Alberda 1965) soluble carbohydrates have been reported for *L. perenne* growing under shade. Soluble sugars and starch (SSS) were consistently lower in the poplar-pasture understorey of the sites examined. Also, the grass component was correlated with the SSS content of pasture in the poplar-pasture area, while in the open pasture area such a relation was not found. Legumes commonly have lower SSS than grasses (van Soest 1994) and the difference possibly widened under shade of poplars. Lower SSS reserves could reduce the C allocation for the multiple plant functions.

5.5.5.3 Carbon allocation

In the present study, lower SSS in the poplar understorey suggested that pasture growing under shade had different C allocation. In soils of high fertility and with the application of fertilisers, preferential allocation of C to leaves has been reported with shading treatments (Cruz 1997a). In addition, increased degrees of shade also reduce root and rhizome yields (Burton et al. 1959). Hodge et al. (1997) using two PAR regimes (350 and 1000 μmol m^{-2} s^{-1}) determined increased ^{14}C partitioning above ground in *L. perenne* seedlings in the low light treatment while total accumulation of dry matter was not altered. Thus, when nutrients were not limiting under shade, C was preferentially allocated to above ground mass. On the other hand, partitioning and translocation of photosynthetically fixed ^{14}C has shown that C substrate translocation for root production increased with decreasing soil fertility under full sunshine (Saggar et al. 1997).

Unfortunately, low soil fertility and moisture interactions with shade have not been determined independently (Belisky et al. 1993, Kephart & Buxton 1993, Wilson & Wild 1995, Devkota et al. 1998). If shoot growth was more important in C allocation, then root growth will be constrained further under shade, limiting the capture of nutrients. Ultimately, total light flux and quality definitively are more important factors in determining understorey growth (Küppers et al. 1996), but the allocation of photoassimilate might be compromised when light and nutrients are limiting.

5.5.5.4 *In vitro* digestibility

In vitro digestibility in the open pasture in the '*main*' and '*late spring*' studies was in accordance to the seasonal variations reported by Barker et al. (1993) for resident hill country pasture. Reduced light has also been reported to increase *in vitro* digestibility (Deinum et al. 1968, Kephart & Buxton 1993), but in the present study it was similar or tended to be lower in the poplar-pasture areas. Reduced *in vitro* digestibility has been attributed to the decrease in the SSS fraction leading to an apparent increase in the cell wall fraction of the cell dry matter (Senanayake 1995).

5.5.5.5 Metabolisable Energy

Because theoretically ME accounts for all nutrients and feed fractions and in this study had a smaller standard error than *in vitro* digestibility or cell wall fractions it was considered a better indicator of the differences between the OP and PP areas on feed value. The energy content of the pasture growing under shade was similar or lower, depending on the date of sampling. With the exception of spring, the ratio of crude protein: metabolisable energy was better in the poplar-pasture area. The higher crude protein per unit of energy was consistent in the sites examined in spring.

Energy and protein are often the most limiting factors for ruminants and have received the most attention in evaluation systems (van Soest 1994). The ratio between crude protein content and the metabolisable energy of pastures is very significant from the nutritional point of view (Martin 1998). The higher protein to energy levels found in managed pastures in New Zealand leads (Johns 1955) to excessive deamination by ruminal microbia causing elevated levels of ruminal ammonia not used by microorganisms (Wang et al. 1996). The higher protein: metabolisable energy ratios calculated for the pasture understorey during spring at the examined sites were likely to impose a metabolic burden to the grazing animals. This finding was supported by a higher protein: metabolisable energy ratio for spring pasture in a 50 sph *P. radiata* agroforest presented by Hawke et al. (1993), but not at other times and other *P. radiata* densities. Because spring pasture production is very important in the New Zealand pastoral production, the worst protein: metabolisable energy ratio in the pasture understorey is more significant that at other times of the year.

The protein: metabolisable energy ratio and small changes in other feed traits may be involved in a decreased nutritional value of the pasture understorey. Besides the fact that grazing animals avoid a shady environment, if given the choice (Naba Devkota personal communication). Sheep and cattle have been reported to dislike the pasture growing under poplars when given the choice to graze away from the trees (Dan White personal communication). Decreased forage palatability also has been reported in cloudy tropical conditions (Burton et al. 1959).

5.5.5.6 Pasture mineral content

The concentration of K and P is known to increase in shaded pastures (Cruz 1997b). With the exception of higher K in the Rongoiti site, the content of Ca, K and P was similar between the open pasture and the poplar-pasture areas in the sites examined in spring. Potassium concentration in pasture of both areas was close to the 2.8% of pasture DM recommended by Smith et al. (1985) for 90% optimal *L. perenne* growth. With respect to K there was a trend for higher figures in the poplar-pasture areas of all sites that might have accorded with the results of Cruz (1997) if *n* had been larger.

The pasture mineral content is normally related to soil fertility and can be used to recommend fertiliser applications (Cornforth 1994). The concentration of K in pasture could be related to the concentration of the mineral in the soil, since K was higher in the topsoil of poplar-pasture areas in the sites with mature trees (see section 4.4.2.1). On the other hand, higher calcium concentration in the soil from poplar-pasture areas did not result in higher concentration in the pasture during the '*late spring study*'. However, data from the seasonal measurements in the Pohangina Hill 1 site showed that calcium content in the pasture understorey was higher than in the open pasture area.

Under conditions of optimum pasture management Ca and P occur at levels sufficient for grazing animals (van Soest 1994). The ratios of Ca:P of the pasture growing under the poplars or in the open were adequate (2:1) to supply daily ruminant minimum requirements of 4 mg/g DM Ca and 2 mg/g DM P (van Soest 1994). In the *'late spring study'*, the Ca:P ratios varied from site to site but were close to 2:1 in both the open pasture and poplar-pasture areas.

K content of pasture was found to be high in relation to Na, particularly in the *'late spring study'*. The Na and K content in the soil was higher in the poplar-pasture area in the Pohangina Hill 1 site, but similar between the open pasture and poplar-pasture areas in the other sites (see Chapter 4). Low Na concentration in the pasture growing under poplars could be attributed to the presence of natrophobe species such as *A. capillaris* and *P. trivialis*. It was possible that Na deficiencies in animals could arise as a consequence of K mineral interaction (Cornforth 1984). McGowan et al. (1995) indicated that the addition of Na as a mineral complement to Na deficient forage increased its palatability. Similarly, fertilisation of natrophilic pasture (*L. perenne*) with NaCl increased pasture and animal production in warm dry conditions (Chiy & Phillips 1991). Thus, the low Na levels in the pasture growing under the poplars might hinder pasture palatability.

5.5.6 Poplar leaf material

Poplar leaf biomass in autumn 1998 totalled 3.1 t ha^{-1}. Leaf litter biomass by poplar (84 DM kg/tree) was within the productivity range (70-90 kg DM yr^{-1} tree) reported for fodder trees in Butan (Panday 1982 cited by Benge 1987). However, autumn tree C inputs into the system may constitute about 80% of above ground and 20% of below ground annual influx (Pregitzer and Burton, 1991). Also, leaf litter biomass increases with poplar age and tree density in the stand (Kaul et al. 1983).

In the present study, leaf fall in March to May was associated with decreased pasture accumulation in the same period caused by physical obstruction of light. Beaton (1981) indicated that with increasing shading and heavier leaf fall, the value of the grazing declined to a lower level as the poplars grew in an agroforest. Fallen tree leaf has not been regarded as a feed in temperate pasture systems (Lowry 1995). However, New Zealand experience shows that poplar leaf material has good foodstuff potential (McGregor 1989, Phipps 1989). Utilisation of shed leaves by grazing in autumn will have a double advantage, as food resource, and reducing the negative effect of physical obstruction of light. Nevertheless, the feed quality of the pasture and poplar leaf litter determined in the present study was barely enough to provide maintenance requirements of livestock.

The leaf litter decomposition rate was not measured but it is known that poplar leaves have high decomposition rates in comparison to pine needles (Taylor & Parkinson 1988a), and that decay rate is primarily temperature and secondly moisture dependant (Taylor & Parkinson 1988b). A decomposition rate of 1.5% per month has been determined over a 24 month period for *P. tremuloides* leaf litter in a cool environment (Louisier & Parkinson 1976). However, higher temperature during winter at the present site should accelerate the initial decay rate until lignin compounds are dominant in the leaf litter composition (Meentemeyer 1978, Taylor & Parkinson 1988a). In a subtropical monsoon climate of the central Himalayan Mountains the turnover time of *P. deltoides* D-121 litter on the forest floor was just above 1 year (Lodhiyal et al. 1995). A New Zealand experiment at Horotiu (E 175° 10': S 37° 41') determined a *in situ* leaf litter decomposition rate of 11.7% month^{-1} for alder (*Alnus glutinosa)* during winter time (Mackay personal communication). A leaf litter decay rate of this magnitude along with drift and conmminution by animals could partially explain the quick recovery of PA rate in September.

Leaf litter from the *P. deltoides* in Pohangina Hill 1 had much lower feed value when compared with the fresh foliage of poplar. However, grazing of shed leaf is the easiest form of utilisation. Pruning can provide yields of 1-5 kg/tree every 2 years (NZPC 1995) Cattle will eat poplar pruning up to thumb size (Wester 1994), but management of branch residue still represents a problem (McLeod 1985). Other management practices such as coppicing are available (New 1985, Hamilton 1997). However, their implementation relies in not imposing constraint on the poplar's primary function in controlling soil erosion (Hicks 1995).

Leaf litter or foliage can be a useful resource of minerals. Poplar leaf litter also can be used to supplement Ca in the diet of pregnant cows during lactation or young calves. The high concentration of Ca in the leaf litter (19 mg/g DM) will require small intakes of the material. The Zn content of poplar foliage (158 µg/g DM) and leaf litter (284 µg/g DM) was 3 and 6 times of the annual range found in pasture (41-62 µg/g DM) in the Pohangina Hill 1 site. Khan (1996) found that Zn level in hill country pasture in winter ranged from 13 to 43 mg/kg DM, depending on Cd background. Zn concentrations in *L. perenne* have been reported in the range 57 to 138 mg/kg DM (AFIC 1987). However, in the *'late spring study'*, Zn levels in pasture were considerable higher (165-462 µg/g DM) at the different sites. Cowperthwaite (1994) also indicated that *P. yunnanensis* had a Zn content of 336 mg/kg DM in leaf litter compared with 35 mg/kg DM for pasture. Zinc oxide is found to be effective in preventing facial eczema at doses of 30 mg /kg body weight (Brightling 1988). Facial eczema has been associated with poor spring management that leaves pastures with low clover and high dead matter content (Clark 1994) during or after periods of warm humid weather between January and April (Mortimer 1987). The problem also has been reported in not very well managed shelterbelts (Gregory 1995). Although comparable information was not available for poplar-pasture systems, it is possible that facial eczema could originate in badly managed poplar agroforests. Thus, the role of grazing management in poplar agroforests in preventing and ameliorating or causing facial eczema needs further investigation.

5.6 Conclusion

A decrease in pasture accumulation under the canopy of widely spaced poplars as a result of shading was observed in this study. The canopy closure ratio of the poplar trees was 70% and was used to determine the potential understorey pasture accumulation as 71% of that in the open pasture. Measured pasture accumulation in the poplar-pasture system was 6.2 t ha^{-1} yr^{-1} or 60% of that in the open pasture. Lower photosynthetic active radiation and topsoil temperature contributed to decreased pasture accumulation. Topsoil water varied around the poplar trunks, but not in a magnitude likely to limit pasture growth. Topsoil water was lower in the poplar-pasture system only in January, May and July. However, soil water potential presumably was higher in the open pasture for longer and more often during the year due to the stoniness of the soil profile. Topsoil water from the poplar-pasture was similar to that in the open pasture during the growing season, notwithstanding the lower effective rainfall that reached the soil under the poplar canopy. It was possible that topsoil water selectively influenced the botanical composition during late spring in the poplar-pasture system when dry conditions prevailed. Nonetheless, pasture botanical composition was similar between the open pasture and poplar-pasture in different sites during late spring. The lower pasture production represented by the legume component of the pasture understorey represented 54% of the N-fixation estimated in the open pasture system. Feed composition of the pasture understorey showed lower soluble sugars and starch content. The ratio of crude protein: metabolisable energy was higher in the pasture understorey and may have nutritional consequences at the metabolic level to the grazing animal. A high K: Na ratio in pasture growing under poplars also may have nutritional or palatability consequences. Animal behaviour and performance studies could help to clarify this aspect.

The influence of the poplar canopy, by shading and leaf litter shedding, was only evident at the sites with mature trees. At the site with young trees, the poplar canopy had a negligible effect on soil water, temperature and pasture accumulation. Some evidence suggested a negative shade by soil fertility interaction that may decrease pasture accumulation. Management options should be developed considering that light and not moisture was the limiting factor for pasture production under mature widely spaced poplars in the moist temperate climate where the examined sites were located. Leaf litter, fresh or senesced had enough nutrients to support animal maintenance requirements. Pruning or harvesting the leaves of trees for fodder will decrease the canopy closure ratio and increase pasture accumulation if soil fertility is not limiting. However, decreasing the poplar leaf area will decrease tree growth and rainfall interception and in turn, accelerate run off and erosion. These relations need further research to clarify management opportunities.

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6. General discussion and opportunities for system development

6.1 Introduction

The primary objective of sustainable land use is enhance agricultural production while conserving natural resources on which production depends (NZMAF 1993). Current pastoral land-use is not considered sustainable in some areas of New Zealand hill country as it contributes to the deterioration of the natural resource base, as a result of soil erosion and chemical exhaustion (Trustrum et al. 1990, DeRose et al. 1993). Despite important previous experience in the use of wide spaced-planted poplars as a land conservation tool in New Zealand pastureland (Miller et al. 1996), there is a need to understand the influence of poplars on hill soils and pasture production. A series of field and studies were conducted to compare the impact of a mature 'poplar-pasture' system with traditional 'open pasture', both grazed by sheep and cattle. The influence of poplars on rainfall partitioning and topsoil water status, topsoil physical and chemical properties and pasture production were discussed in Chapters Three through Five. This Chapter is focused on general discussion of the findings and the implications and opportunities for further system development.

6.2 General discussion of results

Pasture accumulation was lower in the poplar-pasture than in the open pasture system. Poplars increasingly dominated the pasture understorey as they developed and accumulated aerial biomass. However, the poplar-pasture system has the potential to offer a stable feed supply during the summer and autumn in the form of foliage or leaf litter, particularly to compensate lower pasture yield in the open pasture during dry weather conditions. In comparison to traditional pasture land-use, the poplar-pasture system changed the pasture environment by reducing light quantity and quality, increasing soil pH and exchangeable bases and maintaining different water relations. The poplar effects on the environment resulted from different processes, mainly through radiation and rainfall interception and nutrient uptake and recycling. Table 6.1 summarises the benefits and undesirable effects of poplar trees in a poplar-pasture system in humid temperate environment reported in this thesis and recorded in the literature. Higher soil pH, exchangeable bases, water use and lower effective rainfall (throughfall) were identified in this thesis, as desirable effects when compared with stable open pasture. The balance between the benefits of the poplar-pasture system versus the possibility of erosion appears to be clear, but cannot be quantified as a number of externalities are present in the system at the farm and the community level. General discussion of the results obtained are presented in the following sections.

Table 6.1. Summary of desirable and undesirable effects of a widely spaced poplar-pasture agroforestry system when compared with stable open pasture.

Desirable			**Undesirable**			**Research Needs**
	Knowledge[1]	this study[2]		Knowledge	this study	
Soil						
erosion control	NZ/W		fails on steep, shallow soils and dry weather	NZ/W		alternative trees
↑ in pH	O/F	✓				mechanisms
↑ in Ca, Mg, K, Na	O/F A	✓				mechanisms
= organic matter (C)	O/F A	✓				mechanisms
= Earthworms	O/F A	✓				mechanisms
= soil physical prop.	O/F A	✓				animal interaction
↑ spring topsoil water		✓				partition tree/pasture
↓ nutrient leaching		indicative				determine
↑ NO_3^- nutrition		indicative				determine
↑ Water use	O/F A	✓				partition tree/pasture and spatial variation
Pasture growth						
Sustainable, stable production		indicative				determine
			↓ short term DM production	O/A NZ/W	✓	LTS, spatial variation /alternative pastures
			↓ feed value		✓	LTS, alternative pastures
= botanical comp.		✓				LTS, animal interaction
			↓ N-fixation		indicative	determine
			fresh leaf litter		✓	LTS
			water/nutrient competition			determine
Decomposed leaf litter		✓				LTS, animal interaction
Microclimate						
Cooler soils in summer		✓				moisture/shade partition
↓ wind	NZ/S					determine
↓ effective rainfall	O/F	✓				LTS
Transpiration role	O/F A	✓				LTS
↓ runoff						determine, LTS
			↓ light intensity/quantity		✓	spatial variation, LTS
			↓ effective rainfall			determine in dry environments
Animal production						
↓ stress	NZ/F	indicative	shade avoidance if open available	NZ/A	indicative	clarify/animal trials
			different grazing behaviour		indicative	clarify/animal trials
stable feed supply		indicative	↓ feed available		✓	clarify/animal trials
			↓ palatable feed		indicative	clarify/animal trials
emergency fodder	NZ/W	✓				animal trials/R&D
↑ Zn in poplar leaf	NZ/W	✓				facial eczema trials
animal shade	NZ/W	indicative				determine animal behaviour
People						
aesthetically pleasant	NZ/W					determine
			externalities unrecovered			value externality/policy
			no timber industry			R&D

Key: ↑ higher, ↓ lower, = maintain, A agroforestry, DM dry matter, F forestry, LTS long term study, NZ New Zealand, O overseas, R&D research and development, S shelterbelt, W widely spaced.

[1] The area and system where the effect is known to occur or has been reported.

[2] If the effect was explored in the present thesis work (✓) or if the data suggested the effect (indicative).

6.2.1 Canopy effects ameliorating erosion vs. pasture production

Canopy shading had the major influence on the understorey and its microenvironment in the widely spaced mature poplar-pasture system examined at the Pohangina Hill 1 site. When the poplar canopy was in leaf, it had a 70% canopy closure ratio (CCR) and 25% gap area between individual trees (sections 3.4.5 and 5.4.1.1). This implied that the CCR was represented by two atmosphere components: the gap area between the trees and the gaps within the tree canopy. The latter was relatively small because the trees had a leaf area index of 7.3 (Table 3.4). Differentiation of these two kinds of gaps is important because gap areas between trees are a function of tree spacing and age, and gaps within the canopy depend on the canopy architecture of the species, age and silvicultural management.

Radiation intensity under the tree canopy depended upon whether the trees were in leaf or not. Photosynthetically active radiation under the poplar canopy was 20% (10-60% range) of that in the open pasture (5.4.1.1). Canopy shading decreased the understorey dry matter production by 40% and pasture carbohydrate reserves by 17-50% (sections 5.4.1.9, 5.4.1.14, 5.4.2.4 and 5.4.2.7). The shading effect of young poplars at the Ballantrae site had a negligible effect, if at all on understorey pasture production.

Because the mature poplar canopy intercepted 34% of rainfall during springtime it was concluded that this was a major influence on rainfall partitioning and the topsoil water balance. Although throughfall under the tree crown increased with increasing distance from the tree trunk, rainfall interception by the canopy was one mechanism that prevented the topsoil from wetting to the same extent as in the open pasture (section 3.4.3). When topsoil water was already high in springtime and rainfall was moderate and occurred in small events, poplars prevented further increases in topsoil water. Water loss from stem flow was not measured but may have contributed < 3 mm during the period (Helvey & Patric 1965).

Tree transpiration combined with canopy interception and shading determined the topsoil water balance. Tree transpiration contributed to 20-50% of water use from the 0-300 mm soil stratum (section 3.5.1). A precise estimate could not be obtained because it was not possible to differentiate poplar water use from the understorey water use. Although individual poplars extracted a considerable amount of water, probably 60 to 80% was obtained below the topsoil stratum and not competitive with the pasture understorey. Transpiration rates in excess of 400 lt d^{-1} $tree^{-1}$ were recorded and possibly depended on the tree crown architecture and tree position within the stand, in addition to tree size (sections 3.5.2-3). The high transpiration rates probably resulted from increased ventilation and turbulent exchange in comparison to canopies of denser forest stands (Green et al. 1995). Thus, the canopy architecture is as important for evapotranspiration relations as tree density.

Evapotranspirative demand from the poplar-pasture understorey was lower than from the open pasture, because canopy shade decreased understorey pasture production and lowered topsoil temperatures by 2.8-3.5°C (sections 5.4.1.2 and 5.4.2.2). Shading could have a positive effect on understorey pasture production, since longer and higher topsoil water status was likely after the onset of a dry spell. This aspect could be valuable in summer dry temperate climates and needs further exploration. How turbulent exchange influences the understorey is not clear and probably long-term wind runs are more important when comparing pasture understorey and open pasture evapotranspirative demand.

In general, soil water status was more stable throughout the growing season in the poplar-pasture system than in the open pasture. Soil from the poplar-pasture system tended to be drier during autumn and early winter and similar or slightly moister during spring (section 5.4.1.6). No evidence of competition for soil water in the poplar-pasture system was observed in the superficial soil stratum (0-300 mm) where the pasture understorey had most of its growing roots (Appendix II). Under the moist and maritime influenced conditions prevailing in the present study, soil water appeared to suffice for poplar and pasture growth. Notwithstanding, understorey pasture species were unable to capitalise on better topsoil water status in the poplar-pasture system during dry weather (Rongoiti) because lower radiation was limiting growth and not soil water deficit, as occurred in the open pasture (section 5.4.2.3). Canopy shading, by reducing plant transpiration, floor evaporation and soil temperature, adds complex interactions to the soil-water-plant relations that were not possible to determine independently in the field.

Once the poplars have shed their leaves only the shade of tree trunks and branches decrease radiation intensity under the poplar canopy. However, it was not until the leaf litter was removed, or pasture plants emerged through the leaf litter layer that the understorey was able to benefit from the

Figure 6.1. Poplar leaf litter covering the pasture understorey in Pohangina Hill 1 on March 1, 1997.

Figure 6.2. Pasture understorey growing in "full sunlight" under the Pohangina Hill 1 poplars on July 28, 1997. A sunfleck resulting from the hill shade is apparent in the upper left part of the picture.

increased radiation (Figure 6.1). Animals eating or trampling leaf litter were important in accelerating leaf litter decomposition, drift and incorporation into the soil. Pasture fully emerged above the leaf litter layer by mid July and was able to grow unsuppressed by tree shading until early October (Figure 6.2).

Excessive soil water and poor hill stability mainly trigger massive soil erosion in the hill country (Miller et al. 1996). The studies reported here suggest that the canopy of a mature poplar-pasture system had some beneficial properties that ameliorated soil erosion by reducing soil water, mainly by preventing excessive wetting. The tree root system (Hathaway 1973) and the pasture understorey (Young 1997) confer further resilience to the system when the tree canopy is not active or its water buffering capacity is surpassed. Although the major effects of tree transpiration and canopy interception occurs in spring and summer this influence extends into the winter through its lagged influence on the soil water balance (sections 5.4.1.5-6). The effect of leaf litter layer on evaporation and understorey transpiration was not assessed but maybe also has a short-term role in soil stability.

Analysis of rainfall and water use partitioning during the whole year was beyond the scope of the present study. It was assumed that run off and stem flow contributions were negligible during the spring rainfall partitioning study. The contribution to annual water relations of stem-flow, leaf litter rainfall interception and evaporation, and runoff needs to be investigated because they have a role in the autumn-winter period (Helvey & Patric 1965). In addition, pasture understorey evapotranspiration was not determined accurately because water extraction in the topsoil was not independent from the already, and independently estimated, tree transpiration component. The variable and steep nature of the hill slopes used made it difficult to partition tree and pasture contributions to transpiration with the available instrumentation.

Planting and silvicultural management of poplar-pasture systems is highly dependent on the erosion problem and the meteorological conditions, thus a rule of thumb cannot be easily implemented (Figure 6.3). A better understanding of water relations will allow the design of adequate plantings and system resource use while reducing soil erosion. A good appreciation of how tree roots take up water and how the pattern is seasonally and spatially modified (Clothier & Green 1997) will provide a sound base for management recommendations. This knowledge will also be important to determine poplar effectiveness in erosion control and predict drying and wetting fronts and future land stability.

Figure 6.3. Poplar planting in a small gully in the Pohangina Valley during 1997 winter. Pasture or tree management near the landform will be hazardous before the trees attain full development. Better understanding of tree development and water use would provide a good indication about the time when pastoral land use could be unrestricted.

In the current state, the mature poplar-pasture system was able to intercept a considerable proportion of rainfall and still provide sufficient soil water in the superficial soil stratum similar to that of the open pasture (sections 3.4.3-4). This was the result of a low tree density and big individual tree crowns. This signified that although an individual tree used considerable water, the shading effect on reducing floor evapotranspiration was predominant. Similar relations have been presented for Dehesa and Savannah environments where the density of mature, deciduous trees, like oak or acacia, is low and crown area is particularly extended (Belisky et al. 1993, Joffre & Rambal 1993). Also, it has been suggested that shading and rainfall interception are a function of the stand age (Dunn & Connor 1993). As the tree ages, increments in canopy water holding capacity, leaf area index and canopy layer stratification are likely to occur (Watanabe & Mizutani 1996). Eventually, big and old tree individuals will be more efficient in intercepting rainfall and conserving adequate soil water status in the superficial layers. However, in the New Zealand environment, high wind speeds will be a limiting factor to the survival of trees with a big sail area (Figure 6.4).

Canopy shading and leaf litter of a mature poplar-pasture system had a negative impact on pasture production when compared to stable open hill pasture (section 5.4.1.9). The poplar-pasture system examined had no silvicultural management. In the past, the design of the tree plantings was oriented to maximise erosion control while management was initially directed to maximise tree survival. With the exception of the exclusion of mature cattle in the first 2-3 years following planting, pasture management with widely space planted poplars does not differ from open pasture. That is, rotational/set stock grazing based on pasture growth rate and pregrazing pasture mass, and in some cases maintenance fertilisation. Whether or not traditional grazing management, as implemented in New Zealand, is suitable for pasture understorey management still needs to be researched. However, this understorey management may complicate the overall farm grazing management and necessitate further paddock subdivision.

Figure 6.4. Toppled mature poplars in the Rongoiti site after a storm with high wind speeds. Although the trees remained alive, branchwood disposal represents a problem since it has no use for the farmer and is using considerable grazing space. The tree in the foreground had a 1.25 m DBH and 7.8 m height to the first branch.

6.2.2 Trees, soil and nutrient cycling

The most important difference in soil chemistry between the poplar-pasture system and the open pasture was a consistent increase of 0.5-1.2 units in soil pH (section 4.4.2.1). Increases in soil exchangeable bases paralleled pH rise (section 4.4.2.2). The pH difference was also found in the young poplar-pasture system, indicating that nutrient pool allocation could be more important than accumulation over time. It was hypothesised that calcium absorption by poplars was low in comparison to other cations (Liani 1972) and that a large proportion of calcium was recycled in leaf litter (Young 1997). Also, it was assumed that the poplars examined had only NO_3^--N nutrition (Peuke & Tischner 1994) while pasture had a predominant NH_4^+-N nutrition (Whitehead 1995). With these considerations, calcium was represented by a model of an accumulation over time, while N nutrition determined H^+ redistribution in soil and tree pools. Rainfall interception and NO_3^- uptake by poplars could reduce leaching losses of NO_3^-. When N_2 is biologically fixed, acidification will occur only if the fixed N is lost through NO_3^- leaching. The lower light levels under the tree canopy also reduced legume growth and nitrogen fixation as the trees matured (section 5.4.1.13). Reduced effective rainfall (throughfall) in the soil of the poplar-pasture system will also reduce the mobility of the NO_3^- leached, and eventually it could be recaptured by the deeper root system of the trees. These processes require further investigation if the increase in soil pH under poplars is to be fully understood.

In contrast to the marked difference in soil pH, the organic chemistry, excepting N, and physical properties of soil were similar in the poplar-pasture and the open pasture system (sections 4.4.2.2-

4). This occurred despite large differences in pasture dry matter accumulation, pasture composition, litter composition and fall, C and N inputs, and seasonal topsoil water and temperature. Nutrient cycling probably also differed between the two systems and this aspect deserves further investigation. Because no base line data were available for the sites, it is not possible to establish if the soils of these systems were similar prior to tree planting. Several models can be invoked to explain the similarities of soil chemistry in the poplar-pasture and the open pasture systems if the following assumptions are first made.

1. the trees were planted in an erosion prone or eroded landscape;
2. the open pasture areas were not planted in trees because they were on stable land, and had not eroded since the tree planting in the poplar-pasture.

Model 1: soil fertility has a constant relationship over time between the poplar-pasture and open pasture systems. This situation requires that nutrient uptake and cycling to be similar for both systems and similar initial soil conditions prevailed. If the poplar-pasture system has higher nutrient demand, trees can satisfy requirements by complementary nutrient extraction from different soil strata.

Model 2: soil fertility relationships are not constant over time between the two systems. The model represents a situation where there is, initially at least, a build up of a nutrient in the poplar-pasture system while it remains constant, or decreases, in the open pasture. The model will apply when a nutrient is transferred to another nutrient sink or lost from the system. Nutrient transfer from deep soil profiles into superficial ones is another possibility. The model also includes preferential or competitive nutrient uptake between trees and pasture species.

Both models could apply simultaneously for a particular soil characteristic and have an exponential effect over time. Another possibility that complicates the application of the models is the redistribution of superficially transferred nutrients into a deeper soil stratum by faunal activity, or a wider pasture area by grazing animals.

Evidence of nutrient accumulation in the superficial soil stratum in the poplar-pasture system was provided by the soil nutrient concentration of topsoil collected from different strata. The upper 0-20 mm soil stratum in the poplar-pasture system and the open pasture used in the glasshouse experiments was higher compared with the nutrient concentration in the standard field sampling soil depth of 0-75 mm soil used to in the field evaluation (sections 4.4.1 and 4.4.2.3). The poplar-pasture system and open pasture soils had different (not statistically tested) concentrations of P (41 and 21 μg/g of soil, respectively), S (38 and 11 μg/g), K (17 and 6 μg/g) and Mg (60 and 27 μg/g), respectively, in the 0-20 mm topsoil. The similar or lower earthworm activity in the poplar-pasture system (section 4.4.2.5) could imply that nutrient homogenisation in the soil profile had a smaller magnitude than in the open pasture or had not been completed under poplars. In addition, the glasshouse incubation study showed that mixing freshly senesced poplar leaf (at a rate of 9 t DM ha^{-1}) with open pasture topsoil (0-20 mm) raised soil pH within two months of incubation and supported higher herbage growth for eleven months (section 4.4.1). Thus, nutrient cycling through leaf litter probably was an important nutrient pathway under the canopy of individual trees of the poplar-pasture system.

The poplar leaf litter can provide nutrients for the pasture species, however, they will not be readily available when the trees are leafless. Although leaf litter breakdown in the field would be slower in the field than that obtained under the higher temperature and moisture in a glasshouse, the literature indicates that poplar leaf litter decomposes rapidly (Lodhiyal et al. 1995). Assuming a 40% C content in poplar leaf litter (Thevathasan & Gordon 1997), the 3.1 t autumn leaf litter translates into 1.2 t of C ha^{-1} yr^{-1} addition to the soil. This suggested that plant available nutrients decreased during winter since they were immobilised in decomposing litter fall, and then would start to mineralise during spring or summer.

The similar or narrower C:N ratio and lower N inputs in the poplar-pasture topsoil suggested that nitrogen efficiency was higher in the poplar-pasture than in the open-pasture system (section 4.4.2.2). Retranslocation of N and P from the leaves into the tree, before senescence, has been invoked as an important conservation mechanism (Vitousek & Sandford 1986). Higher N efficiency should result particularly when legume population and N fixation decrease as a consequence of the poplar canopy shading. Although rhizobia associated with shade tolerant legumes could benefit from the higher pH in the poplar-pasture when compared with the open-pasture system, the rate of N accumulation would be smaller but the NO_3^- and NH_3 losses would also be smaller.

The present poplar-pasture system had a high Ca, Mg, K soil content and an elevated base cation saturation (sections 4.4.2.1-2). These are some of the positive characteristics associated with the development of mull humus resilient to H^+ loads (Muys 1995). However, a high earthworm biomass also greatly influences nutrient availability in forested stands (Muys 1995). High earthworm biomass and pH close to neutral (6.0-6.5) are associated with profitable pasture production (Springett 1984) and sustainable land use (Lambert et al. 1996) in New Zealand pastures.

Earthworm activity in the poplar-pasture was lower than or similar to that in the open pasture system. It is possible that earthworm activity had different seasonal patterns in the systems studied. Also, other macro or microorganisms could be more important than earthworms in the decomposition process. These aspects deserve further investigation. The general effect of wide spaced poplars on soil properties was considered positive. A better knowledge of the mechanisms and relations, with plant and earthworm populations for example, would be valuable in improving our understanding of the resource allocation and overall performance of the system.

6.2.3 Reflections on the thesis approach and further research

A limitation of the thesis work was the selection of stable open pasture sites as the only witness landform with which to compare the poplar-pasture system. The comparison of the two systems probably did not show the benefits of poplars in soil restoration, but rather compared two systems that are not susceptible to recurrent soil erosion. Implicit in this selection is the possibility of different soil types in the open pasture and poplar-pasture areas resulting from soil erosion. To clearly demonstrate the restorative effect of poplars, contrasting open pasture with different known erosion backgrounds should be used, and planted and unplanted control areas should be compared with uneroded and eroded areas. To determine the preventive role of poplars, non-eroded hills have to be initially compared with and without trees and then wait until the unplanted area erodes. This kind of study needs to span several decades, even if erosion is planned (artificially provoked). In the present study past erosion history and the predominant shade effect of the trees were confounded in the 60-70% reduction in pasture production in the poplar-pasture system when compared to stable open pasture site receiving full sunlight. However, this comparison allowed the establishment of a benchmark for the poplar-pasture system.

6.2.3.1 Pasture production

The modifications to sunlight penetrating the poplar canopy and reaching the understorey floor were the most important factor that affected pasture production. The complex and dynamic nature of light and the limited resources for the thesis work determined that only descriptive and not mechanistic or quantifying measurements of solar radiation were made. The range of measured attributes related to light and shade indicated how important the shading effect was on understorey growth only. However, light measurements had limitations in time and space. How quickly the canopy develops during spring, the variation of canopy structure at different heights, gap development and their relation with light quantity/quality are some issues not explored or measured with limiting instruments in the present study.

A pasture growth model developed as a function of poplar canopy characteristics is an alternative approach to understand canopy modifications to sunlight. It has been shown that pasture DM production and pasture composition in *P. radiata* agroforest changes with stand age and density (Hawke & Knowles 1997). An evident difference with *Pinus* species identified in the poplar-pasture system examined was the marked effect of seasonal leaf fall and decreased tree activity during winter on pasture production. Models such as PC-STANDPACK (FRI 1993) incorporating *P. radiata* and pasture understorey predictors are probably not applicable to poplar stands. Further research must consider stand age and density and seasonal patterns to model pasture production under poplar trees. A plausible and simple non-linear model could be constructed around the CCR, since it is a function of stand age, density and seasonal pattern. Tree canopy management practices could also be easily accounted for in the proposed model. Data from the present work could not provide enough information to construct such a model, because it explored relations of mature trees only. Instead it provided information of a silviculturally unmanaged mature poplar-pasture system typical of many hill areas in New Zealand. This information is valuable because it determined one of the extremes in land use capability of the wide spaced poplar-pasture system. Information from managed stands as well as stands of different age and tree densities are still required to accurately predict pasture production in the poplar-pasture system. The introduction of shade tolerant species adds another avenue to increase pasture when shady conditions cannot be avoided. However, nutritive quality and palatability of pasture growing under shade needs to be researched to maximise its use.

The understorey growth in the poplar-pasture system was higher than that of younger *P. radiata* agroforest at a similar tree density (Hawke & Knowles 1997). This suggest that poplar-pasture systems are likely to be more successful in those areas where pastoral land is the predominant or preferred land use rather than the planting *P. radiata* forestry (Knowles & West 1986, Wilkinson 1996). Research on poplar silvicultural management should be oriented to practices with economic justification, such as maintained or increased pasture production. Although pasture production was only measured for two months under young poplars (Ballantrae site) the evidence suggested that young poplars did not suppress pasture production. Management practices that endeavour to maintain conditions similar to that of young poplar-pasture systems need further research. Research in New Zealand indicates that both pasture production decline and tree growth reduction are possible when the trees are young (Hawke 1991, Gilchrist 1993, Pollock et al. 1994, Yunusa et al. 1995a, Thorrold et al. 1997). Probably it is with young trees that canopy management can be justified economically by the returns in pasture production. Such an understanding of tree growth and pasture production is needed to change the perception of poplar-pasture blocks as run-off pasture for dry stock that are not grazed to full advantage (Hawke 1997).

6.2.3.2 Water relations

The present work showed the importance of the tree component in the water relations of a poplar-pasture system. However, time and methodology constraints limited the scope and precision of the data obtained. The determination of water transpiration by trees was restricted to a short period of time. Seasonal variations are important for water interception and tree transpiration. A more important question that could not be explored was from what soil strata the trees take up water and its seasonal variation. Different studies propose that water uptake by trees can occur in a superficial stratum or at depth (Moreno et al. 1996, Howard et al. 1997) depending on water and nutrient concentration. Also, trees can dynamically change the water uptake pattern according to water availability (Clothier personal communication, Jourdan & Rey 1997). It is evident that water and nutrient uptake influence the distribution of active roots (fibrous) and hence the ability of trees to stabilise a smaller or greater soil matrix in the slope.

It was not possible to determine the extent of competition for water between the trees and pasture nor its seasonal variation in the present study. Soil water in the superficial soil stratum of the poplar-pasture system was adequate most of the time in the main site at Pohangina Hill 1, but this was not the case in other studies (Gilchrist et al. 1993). In the rainfall partitioning study, it was not possible to determine the proportion of water extracted by pasture and the poplars from the superficial soil stratum. However, considering the amount of water extracted by the poplars, the high soil water and the relatively small changes in soil water in the superficial soil stratum, a range for pasture understorey water consumption was estimated.

These shortcomings can be partially resolved with more extensive instrumentation to measure direct transpiration. Heat balance or compensating heat pulse methods can be instrumented in the tree stem and sinker and lateral roots of trees to obtain a spatial partitioning of water uptake by the tree (Green & Clothier 1997). Additionally, heat balance methods can be applied to stems of the herbaceous plants (Gordon et al. 1997). However, assessment of understorey transpiration in a mixed sward conveys additional complications. If the total water use can accurately determined, understorey evapotranspiration can be estimated as the difference of total water use minus tree transpiration (Miller et al. 1998a). Total water use is difficult to measure in a hill and humid environment such as the one examined. Determination of total water use normally involves the installation of wells or neutron probes (Huber & López 1993, Yunusa et al. 1995b), but this was not practical or involved considerable alteration in the hill slope and yet the poplars might be able to take up water from the water table. Other techniques like stable hydrogen isotope analyses can be used to determine sources and uptake patterns of plants (Hall et al. 1998). Models involving the Penman-Monteith equation also require measurement of meteorological data within and above the tree canopy. The installation of a suitable tower will be challenging on an unstable hill slope where high intensity winds prevail. It is possible that combining instrumentation techniques will provide the best error control when establishing source and use of water in tree-pasture systems.

6.2.3.3 Soil characteristics and nutrient cycling

Evidence from the present study suggested that wide spaced poplars intervened actively in nutrient cycling and influenced some properties of the topsoil in accordance with the literature (Thevathasan & Gordon 1997). However, rates of change and the precise mechanisms were not identified in the poplar-pasture system. Some of the beneficial effects of poplars identified in silvoarable (Singh et al. 1989, Park et al. 1994) and forest (Muys 1995, Joshi et al. 1997) systems were also present in the poplar-pasture system when compared to traditional open pasture. Because most of the effects on soil properties reported in the literature have been compared to cropping or forest soils and not to pastureland, it was difficult to compare information in the literature with the poplar-pasture system as a result of change in land use. Despite the lower tree density in the present poplar-pasture system, the trees had an evident and positive effect on soil pH and exchangeable bases.

The similarity or otherwise of soil structure and pore function, organic C, earthworm populations, etc. between the poplar-pasture and open pasture systems could have been explained further if the original soil status of both systems had been known. As commented earlier, higher soil pH in the poplar-pasture system could have originated from younger soil resulting from the exposure of the bedrock after erosion, thus the open pasture will appear old and developed and with a lower pH. At the Ballantrae site, were both systems had similar soil conditions at the time of poplar planting, changes in soil pH were attributed to the poplars. Additional evidence from six other sites with different soil types and tree ages and the data from the incubation experiment support the hypothesis of a poplar effect on pH. Whatever the case, it appears that the trees did not have a negative effect on soil properties.

How poplars alter the nutrient cycles in pastureland deserves further investigation. Groundwater and river NO_3^- contamination is becoming an important issue in New Zealand (Di et al. 1998). Also, it has been shown that poplars can effectively uptake NO_3^- and prevent NO_3^- leaching in an agrisilvicultural system (Browaldh 1995) A similar role could be attributed to poplars in a tree-pasture system. In addition, it has been proposed that poplars could be useful in decreasing the soil concentration of Cd among other heavy metals (Djingova et al. 1995) and undesirable residual pesticides (Burken & Schnook 1997). In this way, poplars could fulfil a multi-restorative function on degraded environments since Cd present in topdressed P fertilisers and NO_3^- contamination and erosion are common problems in New Zealand soils (Brett Robinson personal communication).

As in the case of water relations, the nutrient uptake pattern by the tree roots appears to be critical to the understanding of nutrient cycling by poplars and the final outcome in soil nutrient pools. Although tree roots were present in the superficial soil stratum of the poplar-pasture system examined, nutrients were able to accumulate over time in that soil stratum. This suggested that although nutrients were more concentrated in the surface of the soil, tree roots did not concentrate only in this rich nutrient stratum and continued to extract nutrients from deeper strata. Again, baseline information and sampling of deeper soil profiles would clarify the issue.

The movement of highly mobile nutrients such as S, Na and NO_3^- should be examined in terms of the presence of herbage and tree root systems. The seasonal patterns of nutrient movement and leaching should be explored since trees remain dormant and pasture decreases its metabolism during winter. Also it is possible that nutrient concentrations in the poplar-pasture and open pasture systems followed different patterns. Some evidence of this possibility was provided by the dissimilar earthworm development stages between the poplar-pasture and open pasture systems.

6.2.4 Environmental policy

The current study has shown a number of beneficial effects (i.e. rainfall interception and pH increase) that could be objectively measured and could be used to estimate the value of externalities resulting from the implementation of a poplar-pasture system. On the other hand, it could be assumed that most of the negative environmental effects produced by the poplars are internalised as reduced pasture production. However, there are a number of positive externalities such as reduction in sediment loading, amenity value or reduction in neighbour's fence maintenance costs that are not internalised and the off-site effect is unknown. Although the soil conservation subsidy is one of the few remaining forms of local government intervention in New Zealand agriculture, it varies according to the Regional Council policy. If soil conservation subsidies could be matched to the value of externalities, then "subsidies" will be best termed "economic instruments" that influence the behaviour of land users towards the protection or promotion of the environment, either through financial incentives or disincentives (OECD 1995).

6.2.5 Conclusion

The present study showed that different microclimate elements were modified by the presence of widely spaced poplars in a poplar-pasture system, and indicated how these contributed to 40% decrease in pasture production. Higher soil pH, exchangeable bases and higher soil water status could have a beneficial effect when compared with a traditional pastureland system, but tree shade had a greater effect. The research confirmed the role of a poplar-pasture system in reducing soil water on hill slopes. Seasonal variation in the topsoil water of a poplar-pasture system was observed. Soil under the trees remained slightly wetter and for longer during the growing season and drier when the trees went out of leaf. The poplar canopy was the principal contributor to rainfall partitioning during a short period in spring. The only clear effect of poplars on soil properties was an increase of 0.5-1.2 units in soil pH and exchangeable cations. The complexity of the relations between the elements of the system and the allocation of the system resources made the interpretation of some results more difficult, because information on site characteristics before the trees were planted was not available. The present study advances our understanding of the poplar-pasture system. A number of aspects were integrated which, in the past, have either not been reported or only reported in isolation. Sufficient insight was gained to point out definite areas that require multidisciplinary research. A better understanding of tree-pasture systems is needed before experiments requiring replication can be justified, particularly when the resources required to carry out such an investigation are considerable. Notwithstanding, information from this study and the literature, support the value of poplar-pasture systems in providing soil conservation, fodder, shade, amenity and bioremediation solutions to environmental problems.

6.3 Opportunities for sustainable system development

Adoption and management of poplar-pasture systems are no different from other agricultural systems that endeavour to enable sustainable land use. Both adoption and management should be technically appropriate, economically viable and socially acceptable while not harmful to the environment (Brundtland 1987). Implicit in the concept of sustainable management is the sustainability of each component of the ecosystem, and understanding of their interactions is fundamental (Ong 1996). This is particularly important if capital inputs are limited or if farmers are forced to reduce them (NZMAF 1997).

Early land conservation work in New Zealand was intended to stop soil erosion (van Kraayenoord 1993) with little consideration of the effects of shading on pasture production or regional water yield. Empiricism and caution have partially offset the lack of understanding of forested ecosystems (van Crowder 1996). To date, neither the progressive impact of hardwood agroforest on pasture production (Wall 1997) nor their interactions with the environment (Thorrold et al. 1997) are well understood.

Farmers will be better served by projects providing information on resource requirements, and allocation and performance of agroforest designs (Current et al. 1995) particularly space planted trees. It has been proposed that improved management practice is the most significant factor needed to achieve maximal net social benefit from agriculture (Hamblin & Goss 1993). Indicators that reflect the linkage between sustainable practices and the impact on the environment have been suggested as complementary to the present measures of profitability and success used in the agricultural statistics in New Zealand (Hamblin 1996). Successful management practices also have to minimise risk and tackle the simultaneous problems occurring in the farmer's field with the further constraint of labour.

6.3.1 Poplar forestry or agroforestry?

Silvicultural management of wide spaced poplars to obtain high stumpage of clearwood is possible in New Zealand (Wilkinson 1996) but currently impractical. The main difficulties are the lack of local market for such a product (NZMF 1995), inferior wood quality of the standing poplar stock (Wilkinson 1996), and negligible participation in the international market (Wardrop 1993), which is dominated by products from dedicated plantations in Asia, Europe and North America (FAO 1997). Poplar timber production will require regional organisation in order to provide a continuous supply to local mills and overseas clients; such an organisation does not exist at present.

New poplar hybrids developed in New Zealand have evolved in response to problems encountered with the early poplar varieties used in the 1940-70's period, namely rust and possum, wind and drought damage (Wilkinson 1996). Although the new varieties offer the opportunity to explore multipurpose tree uses (Eyles 1993), farmers still require performance information on the dedicated or alternative uses. At the present time, only anecdotal information provided by farmers' experience is available (Phipps, 1989, Cowperthwaite 1994). How fast farmers adopt widely spaced poplars as a viable alternative to traditional pasture or plantation forestry should be questioned. Tighter farm budgets, and the absence of government subsidies, mean that farmers need better information regarding pasture production under trees, and the likely outcome of tree management alternatives, if they are going to venture in to new technology. This situation becomes crucial for tree planting, given the long-term commitment, and because benefits cannot be weighed at the end of the first season (Current et al. 1995). In addition, the marketing and extension effort by corporate research would be reduced if sound information concerning productivity and management options were available, thus easing pressure in product development and research budgets.

The common concept of agroforestry in New Zealand is very narrow as it refers to *P. radiata* and specifically clearwood production (Hawke & Knowles 1997), and poplar agroforestry has the same connotation. For example, the recommended pruning regime for poplars is aimed to produce clean, knot-free timber (NZFM 1995), but no reference is made in the literature to pruning to optimise erosion control and pasture production. A common expectation when planting trees is to harvest them, but for widely spaced poplars probably this was not the case. To develop "other" agroforestry forms (Nair 1985) with poplars, a different mind set is required to utilise agroforestry to solve problems or satisfy necessities (Reid 1996) and not use pre-established models.

6.3.2 Poplar-pasture management options

The design and management of individual agroforestry systems depends on the precise nature of the outputs and services required as well as the specific characteristics of each farm (Huxley 1996). Sustained pasture production is a desirable output when planting wide spaced trees for land stabilisation. The present study showed that trees decrease pasture productivity when compared to a stable open pasture. Once the primary erosion control objective is achieved, increasing pasture production and/or utilisation should be considered. It is possible that areas planted with poplars can be better used and/or allocated within the farm operation. Better management/utilisation of the resident pasture, the management of the poplar canopy and the introduction of shade tolerant pasture species are some of the possibilities that could be implemented. General characteristics of these management alternatives are discussed in the following sections.

6.3.2.1 Management of resident pasture

Clearly, soil erosion control is the primary function provided by the poplar-pasture system. Pasture production is seen as opportunistic. Higher understorey production, however, would be advantageous to soil erosion control and animal production. If pasture production is a desired output from the poplar-pasture system, management should consider the specific characteristics of the understorey microclimate and/or the understorey growth requirements. If conditions for pasture growth are adequate before tree planting, then future management could be oriented to preserve the production level of the resident pasture by adequate silviculture. In the case of paddocks with mature trees where the canopy cannot be economically modified, tailored grazing management would be the most adequate and pragmatic approach.

The first stage to improve understorey pasture production is to include the paddocks with mature poplars into the grazing roster. Although apparently obvious, some paddocks with mature poplars are not being grazed regularly in many farms. Paddocks with mature poplars should not be considered only as run-off areas. Adequate grazing pressure at all times of the year would help to avoid rank pasture build-up, increase grass and legume tillering and decrease weed encroachment in the understorey.

The spring pasture flush occurs before poplars are fully leaved and is therefore minimally affected by shade of widely spaced poplars (Eyles 1993). Reducing pasture cover at this time will be most beneficial by close grazing with cattle and sheep aiming for a post-grazing mass of 1100-1500 kg DM ha. A hypothetical feed budgets were constructed using the pasture accumulation rates for the 1996-97 growing season obtained at Pohangina Hill 1 site (Appendix V). Because pasture accumulation rate was slower in the poplar-pasture system, it resulted in longer intervals between grazings with beef and shorter with sheep. During autumn, grazing periods with beef would rapidly reduce poplar leaf litter accumulation and the remaining herbage mass could be grazed with sheep before winter.

The common practice of set stocking during spring (Milligan et al. 1987) will be mostly inappropriate, because the pasture understorey has a slower accumulation rate than the open pasture. For the same reason, areas with poplars should be grazed separately from open pasture areas to effectively control grazing pressure. Subdivision or using portable electric fence should solve the problem, but would complicate farming activities. In the long term, planting whole paddocks at even wide spacing could be more economical than managing a multitude of small sections of open pasture and poplar-pasture all over the farm.

Feeding autumn poplar leaf fall to livestock would have a strategic value to the farm operation. It could provide maintenance feed to beef cows in mid pregnancy or ewes in early pregnancy. The practice would allow pasture savings or grazing deferral in open pasture paddocks. Ultimately, grazing management of poplar-pasture systems should consider separate grazing and with different rotation and grazing pressure from that administered in a traditional open pasture system.

6.3.2.2 Canopy management

Ideally, management of the poplar canopy should start when the trees are young (Stace 1996) to maintain the maximum possible productivity of the resident pasture understorey. The poplar canopy can be managed in several ways (von Carlowitz 1991, Hamilton 1997) to ensure erosion control is not compromised, and the economic or strategic benefit obtained from the management is sufficient to compensate incurred expenses. Young trees can be easily pruned up to 6 m height to minimise shading, while thinning can be carried out to decrease the density of the stand (Reid & Wilson 1985). However, about $6x10^6$ poplars have been planted during the last 40 years, and most of them have grown without receiving adequate silviculture (NZPC 1995). Silviculture of mature trees becomes problematic because some trees may need pruning above 6 m and double leaders and presence of tension wood require an expert felling technique. Because many farmers carry out much of the on farm silviculture, the long-term strategy in poplar use should be focussed to develop an integrated farm operation, while minimising the risk and cost involved.

Young poplars can be effectively managed to obtain emergency fodder or maximise pasture understorey production. The first option may also improve pasture understorey production. Depending on the age of the tree, urgency and future management, pruning or felling can be appropriate. For mature trees, felling probably is the best option and after that, the tree can be pruned frequently to obtain a single leader or left to develop a bushy canopy and coppiced regularly. In this case, erosion control would depend only on the well-developed roots of the mature trees and less in the rainfall interception capabilities of the canopy.

Because poplars have to be planted where erosion control is needed, more often than not, they will be exposed to strong winds. Although poplars are known to withstand windy conditions better than *P. radiata* (Evans 1973), highly pruned trees or trees with a big upper canopy will be prone to toppling (Figure 6.4), particularly if root development is limited by disease, wetness or shallowness of the soil (Watson 1990).

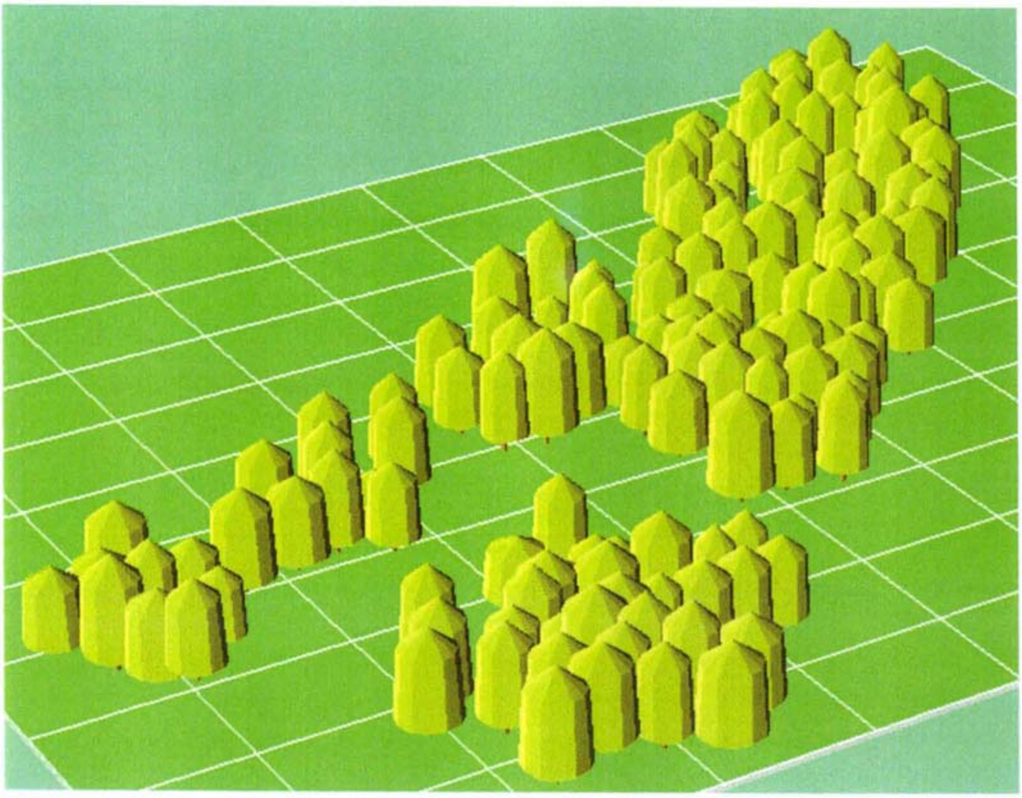
Thinning of mature poplars would increase light for pasture production and provide a very suitable environment for the establishment of a second rotation. Valuable timber, such as *Acacia melanoxy-*

lon (wattles) needs shelter and a certain degree of competition to obtain straight logs (NZMF 1995). Wattles can be planted between mature poplars and if protected with sleeves it is possible that livestock would prefer to rub against the rough bark of the poplars and overlook the wattles. Later in the rotation, poplars could be progressively thinned to favour wattle development. Although the high stumpage value of wattles is certain, it will require a 35 to 45 year rotation to obtain marketable logs.

Short-term income from the poplar-pasture can be obtained from pastoral activity. However, pastoral land use is more sensitive to year to year weather and market variations. To justify any expenditure in canopy management, accurate information on present and future DM production of both pasture and fodder is needed for long term planning of feed supplies and requirements. Estimates of future pasture DM yield can be obtained from direct or indirect assessment of pasture accumulation (Frame 1981) and models considering the CCR (Knowles et al. 1997). On the other hand, poplar fodder DM yield depends on tree age, planting density and silviculture management (Singh et al. 1989, Lodhiyal et al. 1995). Tree inventories can account for these variables, thus only estimates of the DM yield of individual trees at the different stages are needed (Prebble 1998). Tree inventories could reduce the complexity in decision making and assist in the development of a poplar-pasture system utilisation policy.

Management of the canopy of mature trees requires more information and careful planning because any transformation has a long-term effect and mistakes could be difficult to correct in the short term. Information describing forest stands and forest management and disturbance can typically be presented in tabular or graphic form (McGaughey 1997). Visualisation software provides surrogate images that effectively communicate environmental experience (Orland 1994, Thorn et al. 1997) and provide an approachable interface for planning and scenario evaluation. An initial representation of the Pohangina Hill 1 with the Stand Visualisation System (WINSVS v. 3.12, McGaughey 1997) was used to provide management scenarios (Figure 6.5). This software generates graphic images depicting stand conditions represented by a list of individual stand components, e.g., trees, shrubs and cut down material, using detailed geometric models. Although digitised topographic maps can be incorporated in the visualisation, this was not attempted and only a "flatland" demonstration is presented. Tree height, DBH and crown ratios at four aspects along with a generic geometric representation of a mature poplar were used to model individual trees. The visualisation allows the application of silvicultural management, and different scenarios during the life span of the stand (Orland 1994) can be quickly presented if tree growth models are available (Wilkinson 1996). Because all tree information is maintained in a database, a treatment can be applied using a query to

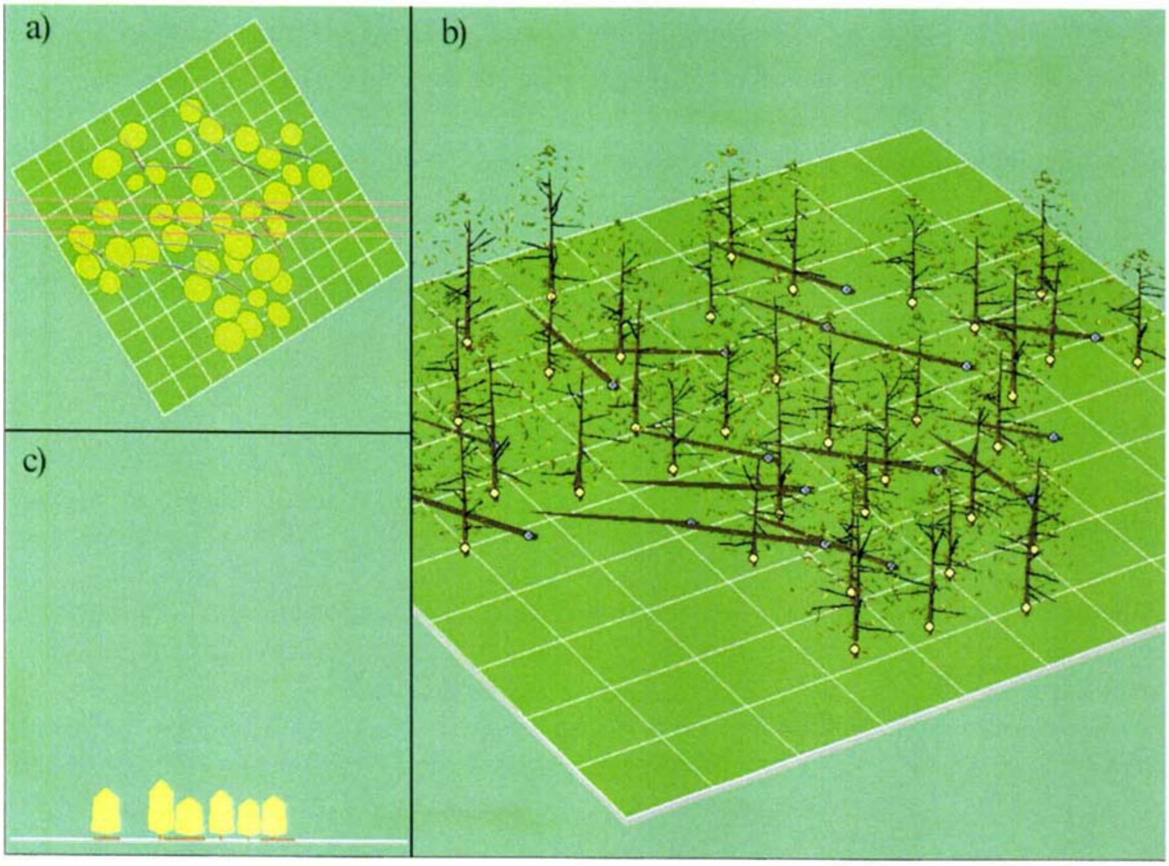
Figure 6.5. Representation of the Pohangina Hill 1 site with WiNSVS viewed from the north. Trees are represented as solid trees using individual tree data and spacings collected from the site. No topographic mapping was used in this illustration and the landscape is shown as a "flatland".



select trees by a given attribute, crown ratios or DBH for example. As an example Figure 6.6 represents a section of the poplar stand displayed in Figure 6.5 where trees have been thinned and left in the ground to decrease the CCR by 10% of the original 70% CCR in spring. The impact of this management practice on pasture accumulation has to be evaluated using a model based on CCR seasonal changes and seasonal pasture accumulation. Although the technique is not applicable at this moment, it provides a quick and sound basis to decide where and which trees need to be managed to increase pasture production. This is particularly important because widely space planting fulfils the requirements of soil conservation and consequently results in uneven spaced trees. For the same reason, pruning and thinning regimes for current poplar plantings need to be modelled and planned on an eroded landform basis and not on a stand basis.

The poplar understorey pasture production model presented by Gilchrist et al. (1993) constitutes advancement in tree-pasture relations because it explored the spatial variability. However, the variability in understorey pasture production is a function of tree age and planting density. To accurately predict the outcome of silvicultural practices on understorey pasture production a model ac-

Figure 6.6. Representation of the central section of the Pohangina Hill 1 site where some trees have been thinned and trunks remain in the field. Trees are modelled as solid areas, the band indicates the area of the cross sectional representation in c). b) Shows an overhead of the same trees but as "realistic trees" considering branching and leaf and branch distribution attributes. c) The profile view view. Standing trees are marked with a yellow dot and downed trees with a blue dot. As in Figure 6.5, the plot is viewed from the north.



counting for spatial and temporal variation is needed. Environmental factors such as rainfall and soil water also have to be accounted for humid and dry regions.

Other factors need to be considered even when assuming that silvicultural management of the poplar-pasture system has no deleterious effect on soil erosion. If shading is partially reduced, pasture production will be increased but increased feed quality of the resident pasture is also necessary. In agreement with the literature (Burton et al. 1959), farm owners of the two sites with mature poplars indicated that animals did not like to graze the poplar understorey. In the present work, it was hypothesised that decreased feed palatability originated from lower pasture content of sodium, soluble sugars and starch and, during spring, a high protein: energy ratio. Higher dry matter (DM) production must be accompanied by a suitable grazing management to avoid accumulation of rank forage and a consequent decrease in future pasture production. Alternatively, animal production might decrease if the animals are not allowed to select their diet. Animal behaviour factors also need to be considered when explaining lower animal preference for the shaded environment. It is possible that flight distance or alertness may be increased under dark conditions (Tanida et al 1996). Therefore, understorey management is as important as the silvicultural management.

If crown size is reduced to decrease shading of the resident pasture species, probably soil water in the superficial soil stratum will decrease as a consequence of higher evapotranspiration from the poplar-pasture understorey (Joffre & Rambal 1993). Also, it is possible that tree debris could negate any pasture yield increment after thinning or pruning operations. Although branchwood (Figure 6.4) could decrease debris runoff and drift while acting as a dam, it will also reduce pasture production, thus disposal of branchwood should be considered when thinning or pruning. Whether or not crown size reduction is accompanied by proportional reductions in throughfall and evapotranspiration demand needs further investigation. More importantly it will be necessary to determine how the different poplar canopy modifications (thinning, pruning, coppicing) affect soil erosion as a consequence of reduced transpiration, interception (Bréda et al 1995) root activity and turnover.

6.3.2.3 Introduction of shade tolerant species

It has been proposed that the success of silvopastoral systems depends on the use and adequate management of shade species (Wong & Stür 1993) because decreasing incidence of photosynthetic active radiation reduces the productivity of a non-shade tolerant understorey (Hawke & Knowles 1997). There are a number of species that are shade tolerant (Gadgil et al. 1986, Jaswal et al. 1993) or are adapted to shady environments (Newman 1997), hereafter called shade species, that could be introduced in poplar-pasture systems. However, for the risk and cost of establishing new pasture to be reasonable, the CCR would be need to be high and productivity of the resident pasture understorey would need to have been reduced. It would be more economical to maintain the resident, non-shade tolerant pasture understorey during the early part of tree development because these species can grow vigorously and even can modify growth of young trees in agroforestry systems (Miller et al. 1998b, Yunusa et al. 1995a), but this will be relative to distance to the tree (Yunusa et al. 1995a, Goh et al. 1996).

Shade species can be considered when trees have to be planted and the tree rotation is very long, or if accessibility or erosion hazard preclude harvesting (Maclaren 1993). Lotus (*Lotus uliginosus*) cv. 'Maku' and cocksfoot (*Dactylis glomerata*) are shade species that can be readily used as pasture understorey (Knowles 1991, Devkota et al. 1998). The cultivar Grasslands Maku, released in New Zealand in 1975, is a tetraploid lotus selection derived from local and winter-active Portuguese material (Frame et al. 1998). 'Maku' lotus longevity and persistence will prevent the colonisation of weeds and low fertility grasses (West et al. 1991). It is probably best combined with a non-aggressive cocksfoot cultivar (Frame et al. 1998). Aggressive cocksfoot cultivars have been shown to decrease *P. radiata* growth and compete actively for moisture when compared with a *L. perenne* understorey (Miller et al. 1998b). Cocksfoot could also provide reasonable DM production during the late autumn and winter when 'Maku' lotus is less active (West et al. 1991).

Annual lotus yields of 3.5 to 5.0 t DM ha^{-1} have been obtained under 5- to 6-year-old *P radiata* at 150 to 600 sph, but decline to 1.0 to 3.0 t DM ha^{-1} at age 11 (West et al. 1991). West et al. (1991) also indicated that the persistence of 'Maku' lotus was greater than that of a white clover based understorey (Percival et al. 1984, Hawke & Knowles 1997). Vigorous stolons and rhizomes allow 'Maku' lotus to recolonise quickly by penetrating through decaying branches and needles (West et al. 1991). Grazing by beef cattle has been successful in about 10^4 ha of 'Maku' lotus oversown *P. radiata* forest (Brown 1988, Dale & Todd 1988). However, recommended management avoids autumn grazing in pastureland (Blumenthal & Harris 1998) or agroforest (West et al. 1991) which will probably be important for poplar leaf litter removal. In addition, long rotations are required to maintain a persistent and competitive lotus sward (Harris et al. 1997).

The condensed tannins of Maku (Robertson et al. 1995) could counteract the higher worm burden found in shaded pastures (Hawke 1991) while increasing the efficiency of use of dietary protein (McNabb et al. 1997).

The introduction of shade species could be a viable option when resident pasture species have been substantially degraded by erosion, although the cost of establishment has to be pondered. These species could also be useful when close planting is required and shading is envisaged early in tree development. The glasshouse experiments showed that lotus and cocksfoot thrive well in the poplar-pasture topsoil given enough illumination. Shade species (e.g. lotus) that can quickly emerge through the leaf litter layer would be a parsimonious approach to increasing pasture understorey production when the resident pasture has been smothered by leaf litter and shade. Nevertheless, grazing management should be adjusted to account for the growth patterns of shade tolerant species as well as the requirements of the whole farm operation.

6.3.3 Conclusion

Management options for widely spaced poplars have to be economically viable and biophysically sustainable. Grazing management recognising that the poplar-pasture system is different from the traditional open pasture would offer the best opportunity to increase utilisation and improve resident pasture productivity. Silvicultural management also can be implemented to reduce competition of mature poplars for light. Silviculture would be most valuable if started from poplar planting. Mature poplar-pasture also can be improved, but special consideration has to be paid to the extra cost and complexity. Mature poplars can be used to provide shelter to other more valuable timber species. Improvement of the mature poplar understorey productivity can be also obtained by introducing shade tolerant species. Management of eroded landforms should consider tree canopy and the role of each individual in stabilising the landform. Grazing of poplar-pasture areas must occur separated from open pasture areas. Alternatively, new poplar plantings could cover the complete area of a paddock regardless if it is stable or not. Suitable silviculture would minimise the poplar impact on pasture productivity and facilitate grazing management at the paddock level rather than at the land-form level. Prediction of understorey pasture production resulting from silvicultural practices is not feasible because spatial and temporal variation of understorey productivity in relation to tree age and planting density has not been studied nor the implications to water relations and land stability.

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Appendix I

Pohangina Valley physiography

Pohangina County is in the northern part of the Manawatu District, North Island, New Zealand. It includes the hill country terraces, and river flats of the Pohangina and Oroua Rivers, which drain the western slopes of the Ruahine Range. Five major physiographic units are recognised in the area: 1) the river flats and younger fans, 2) the low terraces and older fans, 3) the high terraces, 4) the hill country, and 5) the mountain range (Figure I.1, Rijkse 1977). The Pohangina Hill 1 site is located in the low terraces unit (MuH) and had experienced multiple erosion events, loosing the gravel and exposing the sandstone (WrH), particularly in the area planted with poplars.

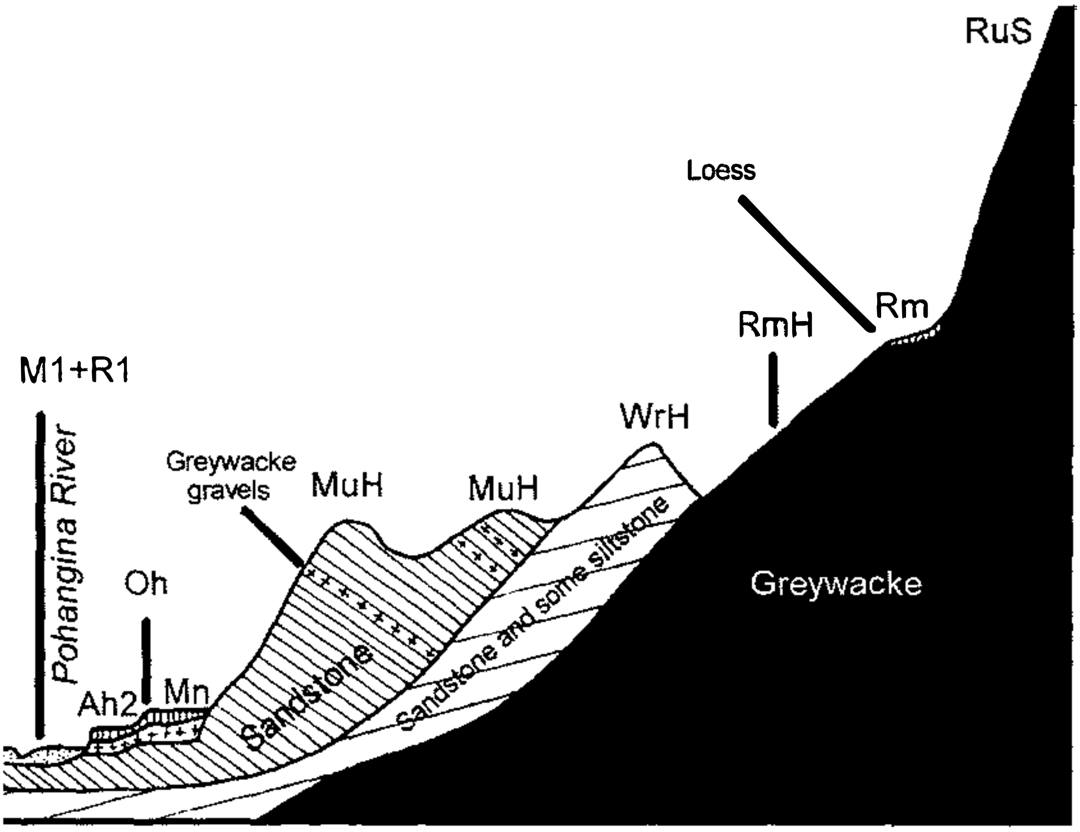

Figure I.1. Idealised cross section of Pohangina County (W-E section near Pohangina Township) to show relationships of soils to physiography and parent rocks modified from Rijkse (1977).

Ah2: Ashhurst silt loam; M1: Manawatu sandy loam; Mn: Milson silt loam; MuH: Makotuku hill soils; Oh: Ohakea silt loam; Rm: Ramiha silt loam; RmH Ramiha hill soils; RuS: Ruahine steepland soils and WrH: Whetukura hill soils.

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Appendix II

Soil profile descriptions for different pits and land forms within the open pasture and poplar-pasture areas at Pohangina Hill 1

Poplar profiles

Profile 1:
Under poplars, headwall of slip.
Aspect: 320°
Slope: 44°
Vegetation: under poplars not much grass sparse cover and poplar leaf litter
Horizons
0-4 cm Ah1 10YR 3/2 very dark greyish brown fine sandy loam; soft; slightly sticky and slightly plastic; moderately developed medium coarse crumb and fine nut structure; abundant fine roots; many worm casts; sharp boundary.
4-11 cm Ah2 10YR 3 brown very fine sandy loam; firm; slightly plastic and sticky; weak fine nut and block structure; common fine to medium poplar roots; gradual boundary.
11-21 cm C 2.5Y 6/1-6/2 light brownish grey; very fine sandy loam; 10% 10YR 4/6 dark yellowish brown fine distinct mottles; moderately loose; no structure; few medium poplar roots; macacaius sands; gradual boundary.
21-100 + cm R 2.5 Y 6/1 light brownish grey; silty very fine sandstone; few olive brown mottles; firm;

Profile 2:
Under poplars, on a nose slope between two slips.
Aspect: 300°
Slope: 36°
Vegetation: weak pasture on shaded pasture.
Horizons
0-2 cm Ah1 10YR 3/2-3/3 dark brown fine sandy loam; very friable; slightly sticky and slightly plastic; moderate coarse crumb, and moderate medium granule; mostly earthworm casts; many fine roots; sharp boundary.
2-20 cm Ah2 10YR 5/3-4/3 brown very fine sandy loam; friable; slightly sticky and plastic; weak fine nut and medium coarse crumb structure; 10% strong brown mottles down root channels; gradual boundary.
20-35 cm CA 10YR 6/2 -6/3 pale brown silt loam; firm; 10% brown worm mottles; 5% strong brown mottles down root channels; weak fine nut and crumb structure, slightly sticky and plastic; gradual boundary.
35-100+ cm R 10YR 6/2 light brownish grey with occasional strong brown mottles; silt loam; firm; weakly thinly bedded with fine sand.

Profile 3:
Under poplars, headwall on slip higher than on profile 2.
Aspect: 250°
Slope: 44°
Vegetation: weak pasture and scattered poplar leaves.
Horizons:

0-3 cm Ahl 10Yr 3/3 dark brown fine sandy loam; very friable; non sticky and slightly plastic; moderate coarse crumb and moderate medium granule structure; many very fine roots; gradual boundary.
3-15 cm Ah2 10YR 4/3 -5/3 brown fine sandy loam; friable; slightly sticky and slightly plastic; moderate medium crumb and weak fine granule structure; many fine roots; sharp wavy boundary.
15-41 cm Bj 10YR 5/6 yellowish brown 15% 10YR 6/3 pale brown 15% fine distinct fine mottles; sandy loam; loose; non sticky and non plastic; weak fine crumb; sharp wavy boundary.
41-100 + cm R 10YR 6/3 pale brown sandy loam; firm; non sticky and non plastic; thinly beaded with silt.

Profile 4:
Under poplars, hummocky midslope on slip.
Aspect 290°
Slope: 18°
Vegetation: weak pasture beneath poplars
Horizons:
0-3 cm Ahl 10YR 3/2 very dark greyish brown; sandy loam; very friable; non sticky and non plastic; moderate coarse crumb and fine granule structure; many very fine roots; gradational boundary.
3-12 cm Ah2 10YR 4/3 Brown with 5% 10YR 6/3 mottles; friable; fine sandy loam; slightly sticky and slightly plastic; weak fine nut and moderate medium crumb structure; common fine to medium roots; gradational boundary.
12-14 cm Bj 10% 10YR 6/3 pale brown 10% 10YR 4/3 dark brown and 80% 1OYR 5/4 yellowish brown medium distinct mottles; fine sandy loam friable; slightly sticky and slightly plastic; medium weak crumb structure; common medium poplar roots; gradational boundary.
14-37 cm C 2.5Y 5/4 light olive brown 10% 10YR 6/3 pale brown with occasional clasts of grey mottled siltstone and fine sandy loam up to 3 cm diameter; fine sandy loam loose; common poplar roots structureless sharp boundary.
37-100 + cm R 2.5Y 5/4 light olive brown 20% 10YR 5/6- 5/8 yellowish brown 20% 10YR 6/3 pale brown 60% coarse distinct mottles; fine sandy loam and siltstone brittle common medium to coarse poplar roots.

Profile 5:
Under poplars, lower part of the slip.
Aspect 330°
Slope: 21°
Vegetation patchy grass cover with scattered leaves.
0-2 cm Ahl 10YR 3/2 very dark greyish brown silty fine sandy loam very friable slightly sticky and slightly plastic; moderate coarse crumb and weak nut structure; abundant very fine roots; gradiational boundary.
2-10 Ah2 10YR 4/3 brown 10% 7.5YR 5/8 -4/6 strong brown coarse distinct mottles; silty fine sandy loam; friable; moderate coarse crumb and weak fine block structure slightly sticky and slightly plastic; gradiational boundary.
10-29 cm Bj 10YR 6/3 pale brown 60% 7.5YR 5/8 strong brown 30% 10YR 4/3 dark brown 10% coarse distinct mottles; fine sandy loam; friable slightly sticky and plastic; weak fine block and crumb structure; many fine to medium poplar roots; gradiational boundary.

29-100 + cm C (slip debris) 50% 10YR 6/1 light grey 30% 7.5YR 5/8 strong brown 20% 10YR 6/3 pale brown coarse distinct mottles; silty fine sandy loam firm; massive breaking to weak coarse blocky structure sticky and plastic; common fine to medium poplar roots.

Open pasture profiles

Profile 6:
pasture between to groups of poplars mid slope
Aspect: 300°
Slope: 31°
Vegetation: pasture.
Note: slope looks more stable but there is a headwall in the upper part of the slope.
Horizons:
0-14 cm Ah 10YR 3/3 -4/3 dark brown very fine sandy loam; firm; slightly sticky and plastic; moderate fine nut and granule structure common worm casts 20% stones up to 5cm greywacke; many very fine roots gradational boundary.
14-25 cm ABw 50% 10YR 4/2 dark greyish brown 30% 10YR 5/3 brown and 20% 10YR 5/6 yellowish brown fine sandy loam moderately firm; non sticky and non plastic; weak fine nut breaking to moderate coarse crumb very stony 50% greywacke sub rounded stones average 2 cm maximum 20 cm; common very fine roots gradational boundary.
25-47 cm Bj 10YR 6/3 - 2.5Y 6/3 light brownish grey sandy loam; loose; weak medium blocky structure with crumbs along roots; 50-60% sub rounded greywacke stones as above many fine roots gradational boundary.
47- 70 + cm C 10YR 6/2 - 6/3 light brownish grey loamy sand; loose; non sticky and non plastic very stony 60% greywacke stones as above (weakly weathered) structureless.

Profile 7:
10 m up slope from profile 6
Aspect: 295°
Slope 28 °
Vegetation: pasture.
Horizons
0-16 cm Ah 10YR 4/3 - 3/3 dark brown fine sandy loam; 15% sub rounded greywacke stones up to 5 cm diameter; slightly sticky and slightly plastic; moderate fine nut and medium crumb structure; many very fine roots; gradational boundary.
16-28 cm ABj 50% 10YR 5/2 greyish brown 40% 10YR 5/4 yellowish brown and 10% 10YR 5/8 yellowish brown coarse distinct mottles; fine sandy loam; very stony 40% sub angular weakly weathered greywacke stones mostly 1 to 2 cm but up to 20 cm; firm; slightly sticky and slightly plastic; weak medium block breaking to moderate coarse crumb; common very fine roots; gradational boundary.
28-54 cm Bwj 70% 10YR 6/4 light yellowish brown 20% 10Yr 6/2 light brownish grey 10% 10YR 5/8 yellowish brown sandy loam; very stony 50% greywacke stones as above; friable; slightly sticky and slightly plastic; moderate medium blocky and medium crumb; few fine roots gradational boundary.
54- 75 + cm C 10YR 6/3 pale brown with a few grey and reddish mottles; sandy loam very stony as above non sticky and non plastic structureless few roots.

Profile 8:
On pasture lower part of the slope
Aspect: 290 °
Slope: 21 °
Vegetation: pasture
Horizons:
0-17 cm Ah 10YR 4/3 dark brown fine sandy loam; friable; non sticky and slightly plastic; moderate fine nut and coarse crumb structure stony with 20% greywacke pebbles 1-2 cm in diameter but up to 20 cm; abundant fine roots with gradational boundary.
17 - 35 cm ABg 40% 10YR 5/2 greyish brown 50% 10YR 6/3 pale brown 10% 7.5YR 4/6 strong brown coarse prominent mottles; fine sandy loam very stony 40% weakly weathered greywacke sub rounded pebbles mostly 1-2 cm but up to 15 cm friable; slightly sticky and plastic; moderate fine to medium block breaking to medium coarse crumb structure; common fine roots; gradational boundary.
35-54 cm Bg 60% 10YR 6/4 light yellowish brown 20% 10YR 6/2 light brownish grey and 20% 10YR 5/8 yellowish brown coarse prominent mottles; fine sandy loam; very stony 35% as above; friable; slightly sticky and slightly plastic; weak fine block breaking to moderate coarse crumb structure; few roots; gradational boundary.
54-90+ cm C same colour as above; fine sandy loam 20% fine greywacke gravel as above; slightly sticky and slightly plastic and massive.

Soil classification
Oroua hill soils in the pasture with gravels greywacke; NZT Orthic Brown Soils.
Whetukura hill soils under the poplars; NZT Mottled Orthic Recent Soils.

Colours according to Munsell soil colour charts.

Survey and interpretation by Dr. Allan Palmer.

Appendix III

Code to model sap velocity using the Beta function

```
Nonlinear Regression

[Variables]
t=col(1)
y=col(2)
d=col(3)
[Parameters]
k1=0
k2=0.8
k3=1.4
k4=2.1
a1=10000
a2=7000
a3=5000
a4=3000
b=3.3
c=0.3
s=0
l=1.2
[Equations]
f=IF(d=1,f1,IF(d=2,f2,IF(d=3,f3,f4)))
f1=k1+a1*((s+l-t)^b)*((t-s)^(b-c))
f2=k2+a2*((s+l-t)^b)*((t-s)^(b-c))
f3=k3+a3*((s+l-t)^b)*((t-s)^(b-c))
f4=k4+a4*((s+l-t)^b)*((t-s)^(b-c))
fit f to y
[Constraints]
k1>0
k2>0
k3>0
k4>0
[Options]
tolerance=0.000100
stepsize=100
iterations=100

where t=time
        y=sap velocity
        d=depth of sap velocity measurement
```

Appendix IV

Forage mineral content of the combined open pasture and poplar-pasture at different sampling dates in the Pohangina Hill 1 site. Forage from the poplar-pasture area had higher ($P<0.05$) content of Ca, Co, and Sr (Table 5.7). Sulphur content was different ($P<0.05$) for pasture from the poplar-pasture and open pasture areas

Mineral	Mar-96	SEM	Jun-96	SEM	Sep-96	SEM	May-97	SEM
				µg/g DM				
Al	633.5a	50.4	215.3b	61.7	558.0a	61.7	594.7a	56.3
As	3.7a	0.1	3.1b	0.1	3.0b	0.1	3.8a	0.1
B	12.3a	1.0	11.4a	1.2	11.7a	1.2	12.4a	1.1
Ca	6183.8a	432.4	6442.8a	529.6	5254.0a	529.6	6398.5a	483.5
Co	0.79a	0.1	0.64ab	0.1	0.3b	0.1	0.9a	0.1
Cu	16.1a	0.9	9.7b	1.1	8.9b	1.1	15.1a	1.0
Fe	469.7a	26.7	214.3b	32.7	502.8a	32.7	442.6a	29.8
K	23776.3a	1961.3	22287.8a	2402.1	24362.3a	2402.1	31702.8b	2192.8
Mg	2442.7a	81.4	1867.0b	99.6	1943.0b	99.6	2259.9b	91.0
Mn	251.4a	27.5	152.9a	33.7	170.0a	33.7	155.3a	30.8
Mo	0.5a	0.1	0.5a	0.1	1.0b	0.1	0.4a	0.1
Na	1558.7a	269.7	1422.5a	330.3	1262.0a	330.3	1257.9a	301.5
P	3743.0a	258.5	2960.0a	316.6	3753.5a	316.6	3502.2a	289.0
Pb	3.0a	0.0	3.0a	0.1	3.0a	0.1	3.0a	0.0
S	3204.0a	193.8	2064.9b	237.3	2271.8b	237.3	3130.5ab	216.7
Se	7.5a	0.3	5.0c	0.4	6.2bc	0.4	6.8ab	0.3
Si	528.8a	21.4	463.3ab	26.2	413.5b	26.2	532a	23.9
Sn	0.9a	0.2	0.6a	0.2	0.6a	0.2	0.9a	0.2
Sr	50.1a	3.5	54.2a	4.3	39.2a	4.3	53.8a	3.9

[1] pooled standard error of the mean

[2] within row and mineral, means with same letter were not different ($P>0.05$).

Appendix V

Hypothetical feed budgets for the poplar-pasture in the 1996-97 growing season at Pohangina Hill 1, with balanced sheep and cattle

Date	Accum. rate kg ha^{-1} wk^{-1}	Pasture cover[1] kg ha	Pregrazing target kg ha	Postgrazing target kg ha	Grazing Class	days to return
1-Aug-96			1500	1000	Sheep	
8-Aug-96	70	1070				
...						
29-Aug-96	70	1280				
5-Sep-96	158	1438				
...						
26-Sep-96	158	1910				
3-Oct-96	127	2037				
...						
24-Oct-96	127	2417	2400	1500	Cattle	84
31-Oct-96	127	1627	1600	1000	Sheep	0
7-Nov-96	110	1110				
...						
28-Nov-96	110	1440				
5-Dec-96	196	1636				
...						
26-Dec-96	196	2224				
2-Jan-97	81	2304				
9-Jan-97	81	2385				
16-Jan-97	81	2465	2400	1500	Cattle	84
23-Jan-97	81	1581	1600	1000	Sheep	0
30-Jan-97	81	1081				
6-Feb-97	84	1165				
...						
27-Feb-97	147	1543				
6-Mar-97	145	1688				
13-Mar-97	601	2290				
20-Mar-97	601	2891	2900	1500	Cattle	63
27-Mar-97	829	2329				
3-Apr-97	401	2730				
10-Apr-97	401	3130	3100	1500	Cattle	21
17-Apr-97	210	1710				
24-Apr-97	210	1920				
1-May-97	117	2037				
8-May-97	85	2122				
15-May-97	35	2158	2100	1000	Sheep	35
22-May-97	22	1022				
29-May-97	22	1045				
5-Jun-97	22	1067				
...	22	1090				
26-Jun-97	22	1134				
3-Jul-97	53	1187				
...	53	1239				
24-Jul-97	53	1344				
31-Jul-97	53	1397				
7-Aug-97	70	1467	1500		Sheep	84

[1] includes poplar leaf litter during autumn.

Hypothetical feed budgets for the poplar-pasture in the 1996-97 growing season at Pohangina Hill 1, with sheep predominance

Date	Accum. rate kg ha^{-1} wk^{-1}	Pasture cover[1] kg ha	Pregrazing target kg ha	Postgrazing target kg ha	Grazing Class	days to return
1-Aug-96			1600	1000	sheep	
8-Aug-96	70	1070				
...						
29-Aug-96	70	1280				
5-Sep-96	158	1438				
12-Sep-96	158	1595	1500	1000	sheep	42
19-Sep-96	158	1158				
26-Sep-96	158	1315				
3-Oct-96	127	1442				
10-Oct-96	127	1568	1500	1000	sheep	28
17-Oct-96	127	1127				
...						
31-Oct-96	127	1380				
7-Nov-96	110	1490	1500	1000	sheep	28
14-Nov-96	110	1110				
...						
28-Nov-96	110	1330				
5-Dec-96	196	1526	1500	1000	sheep	28
12-Dec-96	196	1196				
...						
26-Dec-96	196	1588	1500	1000	sheep	21
2-Jan-97	81	1081				
...						
30-Jan-97	81	1403				
6-Feb-97	84	1487				
13-Feb-97	84	1571	1500	1000	sheep	49
20-Feb-97	147	1147				
27-Feb-97	147	1295				
6-Mar-97	145	1440				
13-Mar-97	601	2041				
20-Mar-97	601	2643	2600	1500	cattle	35
27-Mar-97	829	2329				
3-Apr-97	401	2730	2600	1500	cattle	14
10-Apr-97	401	1901				
17-Apr-97	210	2111				
24-Apr-97	210	2321	2300	1500	cattle	21
1-May-97	117	1617	1600	1000	sheep	0
8-May-97	85	1085				
15-May-97	35	1121				
22-May-97	22	1143				
...						
26-Jun-97	22	1255				
3-Jul-97	53	1308				
...						
31-Jul-97	53	1518				
7-Aug-97	70	1588				

[1] includes poplar leaf litter during autumn.

Appendix VI

Published papers

Guevara-Escobar, A., Edwards, W.R.N., Morton, R.H. and Kemp, P.D. 1997. A model describing sap velocity in Poplars. *Proceedings Agronomy Society of the New Zealand.* 27:9-14.

Guevara-Escobar, A., Kemp, P.D., Hodgson, J., Mackay, A.D. and Edwards, W.R.N. 1997. Case study of a mature *Populus deltoides*-pasture system in a hill environment. *Proceedings of the New Zealand Grassland Association.* 59: 179-185.

Guevara-Escobar, A., Kemp, P.D., Mackay, A.D, Hodgson, J. and Horne, D. 1998. Effects of a poplar-pasture system on soil properties. *In:* New Zealand Soil Society Conference. Gisborne, New Zealand. pp. 169-170.

Appendix VII

Biography

I was born on May 10th 1963 in México City, México. From 1982 to 1987 I studied at the Faculty of Veterinary Medicine and Animal Husbandry, National Autonomous University of México (UNAM), obtaining my B.S. degree in Veterinary Medicine. At the same time I studied Computer Science at Central Computer Services, UNAM. From 1985 to 1989, I worked for the Faculty of Veterinary Medicine and Animal Husbandry, UNAM as lecturer assistant and coordinator of the computer centre at the Nutrition Department, and junior lecturer in Animal Nutrition at the same university. From 1989 to 1995, I studied as part time my Masters degree at the Faculty of Veterinary Medicine and Animal Husbandry, UNAM. In 1990, I obtained a diploma in milk production at the Animal Science Institute, Cd. Habana, Cuba. From 1991-1993 I worked as manager, and from 1993 to 1995, as technical director of the Agriculture and livestock research, extension and education centre of the UNAM. From 1987 to 1995, I worked as independent advisor in dairy, beef and sheep operations. From 1995 to 1998 I undertook a Ph.D. programme at Massey University, New Zealand. After completing my Ph.D. studies, I will go back to México and work for the Faculty of Veterinary Medicine and Animal Husbandry, UNAM.