# ENVIRONMENTAL EFFECTS OF DENSELY PLANTED WILLOW AND POPLAR IN A SILVOPASTORAL SYSTEM

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**ZAKER HUSSAIN**

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***THIS THESIS IS DEDICATED TO MY PARENTS WHO ALWAYS PRAYED FOR MY SUCCESS TO GAIN HIGHER QUALIFICATION***

# Abstract

New Zealand, having large areas of hilly landscapes, is subject to the risk of soil erosion, and summer and autumn droughts that limit pasture growth, which in turn affects the livestock-based economy. The nitrogen and phosphorus input in fertilisers coupled with livestock excreta and soil disturbance impose a serious threat to downstream water quality. The planting of trees is one option used to decrease soil erosion, increase the quantity of forage and manage runoff.

To date, research has mainly focused on wide spaced poplar trees for feed quality and their effects on understorey pasture growth. However, there is increasing interest in the use of densely planted willow and poplar for fodder purpose. The effects of young (< 5 yrs old) willow and poplar planted at close spacing on runoff, soil erosion, growth of understory pasture and nutrient losses have never been studied in New Zealand.

Three field trials (two at Crop and Research Unit, Moginie, Manawatu and one at Riverside Farm, Masterton) were conducted between October 2004 and November 2006 that incorporated comparative establishment and growth of densely planted willow and poplar and their effects on soil moisture, runoff, sediment load and nutrient losses from grazed and fertilised farmland.

It was concluded that densely planted willow and poplar (3-4 yrs) reduced total nitrogen (TN) and dissolved reactive phosphorus (DRP) by 47 % each and sediment load by 52 %. Young trees reduced surface runoff and soil moisture more as they aged. However, due to their deciduous nature willow and poplar were not effective in reducing surface runoff in winter and early spring. Sheep preferred camping under trees, especially in late spring and summer, and this led to greater deposition of dung and urine under trees than open pasture. Sheep grazing, especially in winter, significantly increased sediment and nutrient loads in runoff water. The N and P fertiliser application increased nutrient load in runoff water well above the threshold level required to initiate algal growth to create eutrophication.

Densely planted willow and poplar significantly reduced understorey pasture growth by 23 % and 9 %, respectively, in their second year at Moginie, mainly due to shade, but coupled with soil moisture deficit in summer. The pasture growth in a willow browse block was 52 % of that in open pasture as a result of shade and differences in pasture species composition. Sheep browsing reduced willow leaf area significantly. Willow and poplar survival rates were similar ($P > 0.05$) after two years of establishment (100 % vs 90.5 %, respectively). However, willow grew faster than poplar in height (1.90 vs 1.35 m), stem diameter (43.5 vs 32.6 mm), canopy diameter (69 vs 34 cm) and number of shoots (8.7 vs 2.3) at the age of two years, respectively.

The research clearly demonstrated that densely planted young willow and poplar trees can reduce runoff, sediment load and nutrient losses from farmland to freshwater, but shade and soil moisture can limit pasture growth under trees. It is recommended that willow and poplar should be planted at wide spacing on the whole farm to minimise loss of pasture. Where blocks of trees are necessary, such as willow browse blocks, sheep browsing can be used as a tool to reduce shade to improve pasture growth. Livestock access to riparian strips should be minimal to avoid livestock camping that can have deleterious effects on water quality.

Key words: willow; poplar; growth; nutrients; pasture; runoff; soil erosion; soil moisture; fertiliser; water; sheep; browsing; camping.

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# Glossary and Abbreviations

**ANOVA:** analysis of variance.

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

**$^{o}$C:** centigrade.

**$cm^{-3}$:** per cubic centimetre.

**cm:** centimetre.

**Canopy:** the part of a tree consisting of branches and foliage.

**DAP:** diammonium phosphate.

**DM:** dry matter.

**d.p:** decimal point.

**DOP:** dissolved organic phosphorus.

**DIP:** dissolved inorganic phosphorus.

**DRP:** dissolved reactive phosphorus.

**Densely planted:** in this thesis it refers to pastureland planted with >6000 trees per hectare.

**dia:** diameter.

**g:** gram.

**GLM:** general linear model.

**h:** hour.

**ha:** hectare.

**ISS:** inorganic suspended solid.

**Kg:** kilogram.

**L:** litre.

**LSD:** least significant difference.

**m:** metre.

**mg:** milligram.

**mm:** millimetre.

**N:** nitrogen.

**NHA:** net herbage accumulation.

**$NH_4^+$-N:** ammonical-nitrogen.

**$NO_3^-$-N:** nitrate-nitrogen.

**OP:** open pasture.

**OSS:** organic suspended solid.

**P:** phosphorus.

**PAR:** photosynthetically active radiation.

**PP:** poplar pasture....pastureland planted with poplar trees

**RCB:** refers to experimental design as randomised complete block

**SAS:** statistical analysis system.

**SEM:** standard error of mean.

**SSP:** single superphosphate.

**TKN:** total kjeldahl nitrogen.

**TN:** total nitrogen.

**TP:** tree pasture...pastureland planted with trees.

**TP:** total phosphorus.

**TSS:** total suspended solid.

**WP:** willow pasture....pastureland planted with willow trees

**yr:** year.

**yrs:** years.

**Zone 3:** the centre of four nuclei trees planted at a square grid.

$\theta$**:** soil moisture content.

$\omega$**:** soil volume at a given depth.

**µg:** microgram.

# GENERAL INTRODUCTION

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## 1.1 Background

A significant proportion of New Zealand's 27 million hectares (Stats, 2006) is hilly or mountainous and one third of the land area is above 1000 m elevation (Tomlinson, 1992): much of this area is subject to soil erosion. Therefore, New Zealand's rivers carry a staggering 400 million tonnes of sediment from the land to the ocean every year (Hicks & Griffiths, 1992). Rainfall has been responsible for massive slips and landslides, especially in hill country (Benn, 2005; Korup, 2004). Major sediment-producing storms (> 150 mm) occur on a regular basis (Page et al., 1994). The March 1988 Cyclone Bola and February 2004 storms in Wanganui-Manawatu are examples of such storms. Research has shown that total storm rainfall and storm sediment thickness are highly correlated (Page et al., 1994). A review on earthflows by Marden et al., (1992) showed strong, coherent, spatial movement patterns within individual flows with surface velocities ranging from 3.6 to 20.4 m $yr^{-1}$ in North Island, New Zealand.

In New Zealand, agriculture is the biggest land use with 54 % of the land area under grass (Stats, 2005). Livestock (dairy and beef cattle and sheep) are grazed on these pastures for most of the year. The deposition of dung and urine from these animals contributes to increased nutrient losses (N and P) in drainage and runoff waters that impair fresh water quality (Houlbrooke et al., 2004; Houlbrooke et al., 2003; Wilcock et al., 1999). Furthermore, dung deposition from grazing animals causes a significant increase in the concentration and load of harmful bacteria (Fenlon et al., 2000; McDowell et al., 2006a). Soil disturbance and compaction by animal hooves can affect soil physical properties, increase soil erosion (Nguyen et al., 1998) and P loss due to a decrease in aggregate stability (McDowell et al., 2006b).

The N and P losses in surface runoff and drainage water are accelerated as a result of fertiliser application to hill country (Gillingham & Gray, 2006; Gillingham & Thorrold, 2000; Ledgard et al., 1999). The loss of P represents a potential hazard to surface water quality leading to eutrophication (Correll, 1998; McDowell et al., 2004) while N fertiliser may also increase the nitrate concentrations in ground water thereby affecting drinking water quality (Ledgard et al., 1996). The dissolved forms of P such as dissolved organic phosphorus (DOP) and dissolved reactive phosphorus (DRP) in fresh water are readily available for uptake by algae and cyanobacteria and their growth causes green turbid water with limited transparency (McDowell & Koopmans, 2006). The ecological value of eutrophic surface waters is reduced, making recreation less attractive and restricting the use of such water for fisheries, industry, and drinking (Sharpley et al., 1994).

Parts of New Zealand are also subject to severe drought in summer and autumn and future predictions about the impact of climate change on drought frequency and severity are far from encouraging (Salinger, 2000). Droughts have serious economic implications for New Zealand (Tait et al., 2005). For example, the costs of the drought in 1997-98 were estimated at $1 billion (Stats, 2007). Therefore, alternative fodder sources especially in drought prone hill country are vital for future agricultural production.

Trees, especially willow and poplar, when integrated into a silvopastoral arrangement can potentially mitigate soil erosion, nutrient losses and forage shortage. Soil erosion, especially landslides, occur when shear stress exceeds shear strength of the soil, and tree planting has been reported to improve soil strength through root re-enforcement (Ekanayake et al., 1997; Ekanayake et al., 2004). An assessment of soil conservation measures after Cyclone Bola revealed that trees substantially reduced physical damage caused by the storm compared with treeless catchments (Hicks, 1992). The question of "how much do trees reduce landsliding" was answered by Hawley & Dymond, (1988) through computer processing of digital imagery applied to aerial photographs of hillslopes on which widely spaced trees and eroded scars were visible. These authors estimated that landslide scars tended to occupy areas away from the trees and predicted that trees planted on a 10 m grid with 100 % establishment could have reduced storm damage by at least 70 %. Similarly, an investigation of the ability of trees including willow and poplar to control soil erosion at 278 sites has shown that both species have successfully controlled earthflows at 63 % sites and gully erosion at 42 % sites in New Zealand (Thompson & Luckman, 1993). Marden et al., (1992) reported that earthflow rates were 2-3 fold less in forested land than open pasture. However, the effect of trees on soil erosion depends on tree age and spacing. For example, it has been reported that a tea tree stand on the East Coast reduced landslide damage by 65 % at the age of ten while damage was reduced by 90 % when the trees were twenty years old (Bergin et al., 1995).

The current trend of creating willow fodder blocks, encouraged by the Sustainable Farming Fund (SFF) Fodder Tree Project (Charlton et al., 2003) is likely to increase the use of densely planted willow and poplar blocks (Douglas et al., 2003; Pitta et al., 2006), as opposed to the focus of previous research on widely spaced poplar (Douglas et al., 2006; Guevara-Escobar, 1999). The environmental effects of densely planted young (< 5 yrs) willow and poplar on understorey pasture quantity and quality, surface runoff, soil erosion and nutrient losses have not received any research attention in New Zealand. Therefore, this thesis attempts to validate the hypothesis that young, densely planted willow and poplar reduce soil erosion and nutrient loss with only a manageable decrease in understorey pasture growth. This research will be relevant to those contexts in which densely planted willow and poplar are likely to be employed including; as browse blocks on wet slopes (often at the toe of steeper hills), for highly erosion prone slopes and gullies, and riparian strips. The general structure of the thesis is outlined in Figure 1.1.

## 1.2 Objectives

The specific objectives of this thesis are:

(1) Determine the effect of densely planted willow and poplar on soil moisture at different depths.

(2) Study the effect of densely planted young willow and poplar on understorey pasture growth with regard to shade and soil moisture.

(3) Quantify the impact of willow and poplar on surface runoff, soil erosion and nutrient loss.

(4) Determine the effect of willow and poplar on nutrient losses in drainage water.

(5) Determine the effect of sheep grazing on sediment and nutrient loss in a densely planted willow-poplar based silvopastoral system.

(6) Study the effect of fertiliser application on nutrient losses in runoff and drainage in a densely planted willow-poplar based silvopastoral system.

(7) Compare willow and poplar establishment and growth when planted densely.

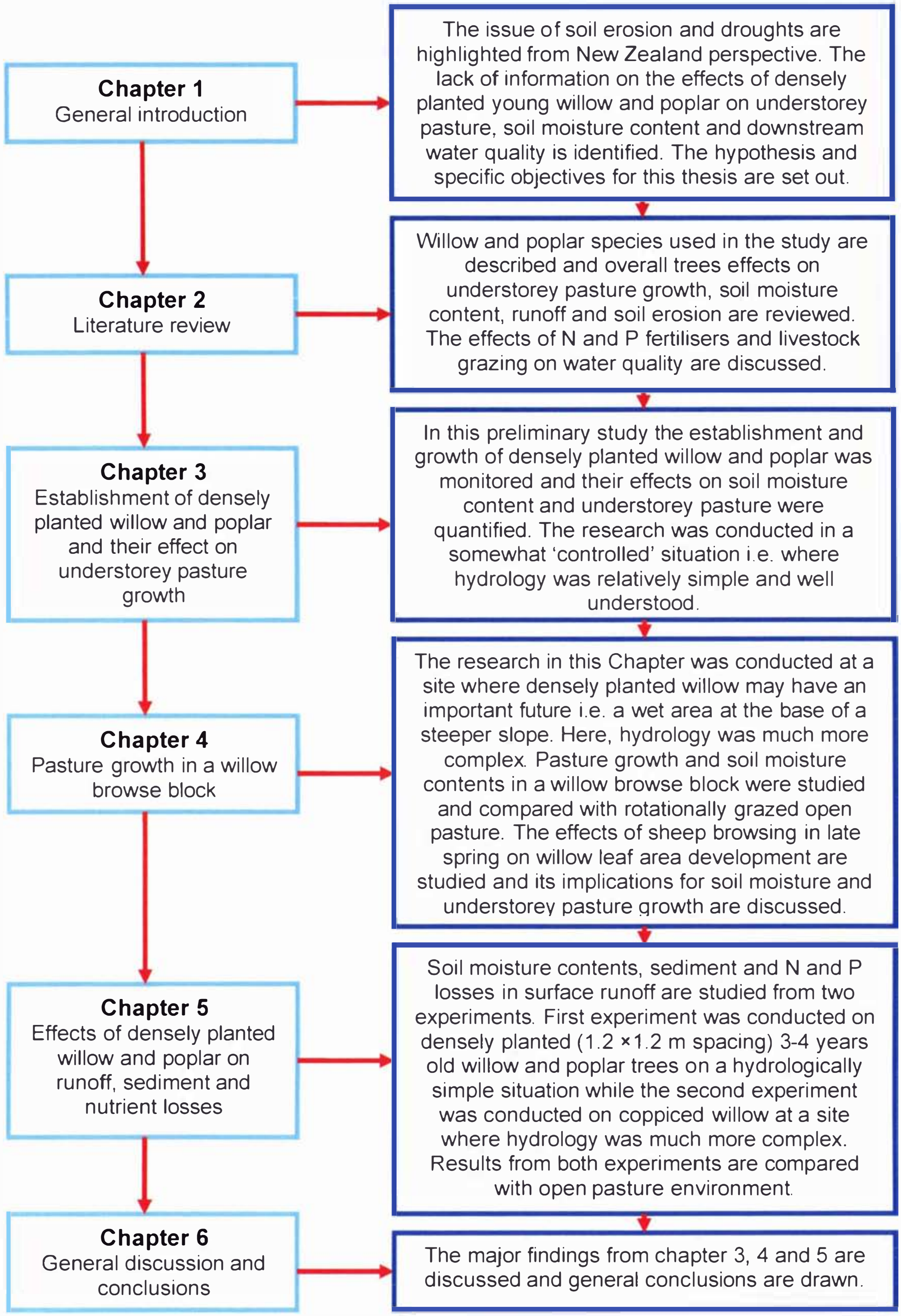


Figure 1.1 Outline of the Thesis.

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# LITERATURE REVIEW

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## 2.1 Introduction

Willow and poplar are a common feature of the pastoral landscape in hill country, New Zealand. Several co-operative studies involving the Ministry of Agriculture and Fisheries and the Forest Research Institute led to the commencement of agroforestry in the late 1960s in New Zealand (Granel et al., 2002; Hawke, 1991; Klingensmith & Vancleve, 1993). The Resource Management Act (RMA) 1991, promotes sustainable management of natural resources and demands regional councils to provide greater regulatory control over water quality, making it obligatory to take practical steps for soil conservation (Selvarajah, 2003).

Tree planting is widely encouraged for sustainable management of pastoral land due to their mitigating properties (Mead, 1995). Nutrient losses to surface water from soil under silvopasture are smaller than those under treeless pasture because of greater nutrient uptake by the trees (Nair & Kalmbacher, 2005). However, trees interact with other components of a silvopastoral system through a variety of mechanisms (Sharrow, 1999) that lead to many advantages and disadvantages and make this system difficult to design and manage.

This literature review is intended to explore the available information regarding tree pasture systems and its environmental implications. Section 2.2 describes willow and poplar species and their distribution around the world. It also gives an overview of willow and poplar use under New Zealand conditions. Section 2.3 and 2.4 give a brief introduction to some environmental effects of trees in a tree pasture system including pasture production and soil water use, while section 2.5 is about the soil erosion status in New Zealand hill country.

Section 2.6 and 2.7 focuses on the importance of P and N to the soil-tree system and their losses through soil erosion, surface runoff and drainage. This section also addresses the environmental implications of P and N fertilisation and animal grazing in a silvopastoral system. Section 2.8 discusses the effect of landuse (particularlyy those involving trees) on sediment and nutrient losses. The effects of animal treading on the soil physical and chemical properties that could alter surface runoff and drainage are discussed in section 2.9. Finally, section 2.10 summarises the findings in the reviewed literature.

# 2.2 Willow and Poplar

## 2.2.1 Distribution and species

Willow and poplar are the dominant members of genus *Salix* and *Populus* in the *Salicacae* family, respectively. The temperate and cold regions of the northern hemisphere are the natural habitat of the genus *Populus* (Van Kraayenoord, 1993) and *Salix*. However, *Salix* is more widely distributed than *Populus* and occurs naturally in the southern hemisphere as well (FAO, 1979).

There are more than 35 species in the genus *Populus* including aspens and cottonwoods (Bean, 1977). The North American species with the exception of *P. balsamifera* are denominated as aspens and cottonwoods (Kennedy, 1985). Poplar are fast growing trees and are indigenous to China, Europe and North America (Ou et al., 1997; Reid & Wilson, 1985). Generally, poplar require moderate levels of soil water for their growth (Miller & Wilkinson, 1995). Similarly, willow prefer moist and cool sites and are usually found in wetland communities. Christchurch Botanical gardens imported over 60 species and varieties of willow from Kew Gardens in 1937, and they were established widely throughout New Zealand for soil conservation purpose (Wilkinson, 1999).

## 2.2.2 Distinguishing features

Willow and poplar share many characteristics and belong to the same family (*Salicacae)*, yet they belong to different genera because of some distinguishing features (Table 2.1).

Table 2.1 The distinguishing features of the genus *Populus and Salix*.

| | Poplar | Willow |
|---|---|---|
| Leaves | Triangular-lozenge shaped, Sometimes round or lanceolate. Long petiole. Foliar polymorphism. | Always long; oval, oval lanceolate. Short petiole. Uniform in shape. |
| Shoots | Circular or angular. Pith cross-section pentagonal. | Circular. Pith cross-section circular. |
| Flowering | Before leaves. Catkins pendulous. Flowers: Oblique perianth, cup shaped without nectarines. Stamens numerous, 5 to 50, with usually reddish anthers. | Before or after leaves. Catkins erect. Flowers: Perianth usually absent but 1 or 2 nectarines (pollination by insects).Stamens few, 2 to 8, with usually yellow anthers. |

Adapted from: (FAO, 1979)

### 2.2.3 Means of propagation

#### 2.2.3.1 Natural fertilization

Willow and Poplar are dioecious woody plants (FAO, 1979) and can reproduce by sexual and asexual means. The male and female flowers are quite small and are produced on separate trees (Bean, 1977), packed into catkins (Kennedy, 1985). Willow and poplar can also hybridise. *Populus deltoides* remains the most widely planted (FAO, 1979) and hybridised species in the genus. Wind pollination is common in *P. deltoides* while the seeds can also disperse through wind and water. Most species of willow introduced to New Zealand comprise of a single sex. Therefore, sexual reproduction happens between male of one species and female of another species (Harman, 2004 ).

#### 2.2.3.2 Vegetative means

Willow and poplar are known for their ease of vegetative propagation compared to other trees planted on pastoral land (Hathaway, 1973; Thompson & Luckman, 1993). The high establishment success and the possibility of quick resumption of grazing following planting (Wilkinson, 1993) make these species most suitable for a silvopastoral system. In New Zealand, three stock types are used for poplar establishment; poles (3 m), rooted cuttings from trees usually 1.5-2 m long and, 1 m stakes (Stace, 1996; Van Kraayenoord & Hathaway, 1986). Poles and stakes don't have the roots at planting time. A pole is rammed to 1 m depth (Wardrop, 1996) while a cutting is planted at 25-35 cm depth (Evans, 1973).

Willow and poplar are established conveniently using either rooted or unrooted stem cuttings (Shelton, 1994). However, the use of unrooted stem cuttings as a planting stock is now more widely practised for willow and poplar. The unrooted cuttings of willow *(Salix matsudana* × *alba* and *S. kinuyanagi)* produce as much foliage as the rooted cuttings, the former being cheaper to establish (Oppong, 1998) and easy to handle. Stem cutting size affects the establishment and growth of any species. Douglas et al., (2003) reported higher total shoot dry matter, regrowth shoot length and canopy width for willow from 2 m poles than 1.1 m stem cuttings at a cutting height of 0.5 m and above.

## 2.2.4 Description of willow and poplar species used in this study

### 2.2.4.1 Tangoio willow

*Salix matsudana Koidz. x alba* L. clone Tangoio is the most drought-tolerant of a range of hybrid tree willow developed in New Zealand (McCabe & Barry, 1988) and has been selected for shelter and soil conservation purposes (Hathaway, 1986a). Tangoio was released in 1980 for farm and horticultural shelter, coded as NZ 1040 (Douglas et al., 1996) with a relatively narrow crown (Plate 2.1).

Plate 2.1 Tangoio willow growing at the Moginie block, Massey University, Palmerston North, New Zealand

This species can be established on hillsides and can sustain high wind pressure. The foliage is palatable to sheep, goat and cattle (McCabe & Barry, 1988) and can be grown on a short rotation coppice system. Like *Salix kinuyanagi,* Tangoio also likes moist sites but can perform well under dry conditions as well. The edible dry matter production after 1.5 years of planting has been reported as 1.12 t DM $ha^{-1}$ and 0.3 t DM $ha^{-1}$ for moist and dry sites, respectively (Douglas et al., 1996).

#### 2.2.4.2 Kinuyanagi willow

*Salix kinuyanagi*, a leafy osier type willow (Slui, 1990), originated from Korea (Oppong, 1998). However, its introduction to New Zealand was via the United Kingdom as a single male clone coded PN 386 (Douglas et al., 1996). This species is potentially suitable for grazing on flat to gently sloping terrain. It tends to be a small spreading tree with leaves that are silvery underneath (Plate 2.2).

Plate 2.2 Kinyoyanagi willow growing at Massey University's Riverside farm, Near Masterton, New Zealand.

The forage has relatively high lignin content (67-95 g $kg^{-1}$ DM) with moderate nitrogen content (21 g N $kg^{-1}$ DM) (Douglas et al., 1996). *Salix kinuyanagi* develops high condensed tannin content that affects its palatability, especially during mid summer (Oppong et al., 1996). This species grows fast in moist conditions compared to dry sites. The dry matter production after 1.5 years of planting can reach up to 1.71 t DM $ha^{-1}$ and 0.14 t DM $ha^{-1}$ for moist and dry sites, respectively (Oppong et al., 1996).

#### 2.2.4.3 Veronese poplar

Veronese is a *P. x euramericana* hybrid black poplar that was originally imported from Italy. Veronese is a straight stem tree with a narrow crown (Plate 2.3). Growth is fast and the tree can attain a maximum height of 30-40 metres. Veronese is wind tolerant and prefers open sites where it is less likely to get rust during a humid period. It is not as palatable to possums as some other clones. Veronese exhibits spectacular leaf colour at flushing. It can tolerate drought better than many other poplar. Veronese is a useful soil conservation tree due to its potential to establish and grow well on more exposed sites. It is also useful for shelter and amenity due to its wind tolerance and upright form (HBRC, 2006).

Plate 2.3 Veronese poplar growing at the Moginie block, Massey University, Palmerston North, New Zealand.

#### 2.2.4.4 Dudely poplar

Dudley is a hybrid of *P. deltoides X P. nigra* and is a male clone (Plate 2.4) used commonly on the East Coast regions for soil stabilisation where its lower resistance to rust is not so important. It has only a few heavy branches so is not so vulnerable to wind like some other clones with heavier branching. However, these trees can cope with drier sites and are used more at lower altitudes. Its fast growth, upright form, narrow angle between branch and trunk, and drought resistance are the acceptable attributes for fodder and soil conservation (I. McIvor, Scientist, HortResearch, Palmerston North, personal communication).

Plate 2.4 Dudely poplar growing at Moginie block, Massey University, Palmerston north, New Zealand.

### 2.2.5 Purpose of planting willow and poplar in New Zealand

Since willow and poplar are exotic to New Zealand, their introduction is based on the need for fast growth, soil conservation, shelter for livestock and fodder requirements in extreme droughts. *P. deltoides* (cottonwood) and *P. nigra 'Italica'* (Lombardy) were first introduced to New Zealand between 1840 and 1850 (Van Kraayenoord, 1993).

### 2.2.5.1 Soil conservation

In New Zealand, large areas of agricultural land are susceptible to erosion (Kelliher et al., 1995), mostly due to forest clearing for agriculture. Planting of conservation trees, particularly willow and poplar, has been used as a tool to cope with this situation and to maintain pastoral farming (Miller et al., 1996; NZMF., 1995). In New Zealand, *P. nigra* and *P. deltoides* have been introduced mainly for soil conservation and amenity purposes (Miller & Wilkinson, 1995).

Willow and Poplar are widely used for erosion control on unstable hillsides (Plate 2.5) due to ease of vegetative propagation, establishment, fast growth, and extensive root system that can readily stabalise large soil masses (Wilkinson, 1999). In hill country, slips and slides occur when the soil has a large water content. Rapid discharge of soil water can significantly reduce the extent of soil erosion. Relative to pasture, tree willow and poplar can remove large quantities of soil water through evapotranspiration (Wilkinson, 1999): this characteristic makes these species suitable for soil erosion control.

Trees reduce the erosive impact of rainfall through reinforcement of the soil (Ekanayake et al., 1997), removal of excess soil water and rainfall interception. In New Zealand, willow and poplar along with *Pinus radiata* are extensively used for erosion control (Fransen & Brownlie, 1995). However, the planting intensity and method of application differs between these species. *P. radiata* has been planted as block or blanket forestry (Maclaren, 1993) due to commercial interest and well established timber markets while willow and poplar tend to be restricted to small blocks where they are widely spaced (Hicks, 1995; NZMF., 1995), However, trees and grass cover both contribute significantly to the reduction in soil erosion (Selvarajah, 2003).The influence of the trees in reducing soil moisture over the growing season extends the capacity of the soil to absorb water during the wetter autumn and winter months when plant water use is very low and risk of erosion is highest (McIvor et al., 2003).

Plate 2.5 Stabalising hillslopes with poplar in New Zealand.
Adapted from: http://www.horizons.govt.nz/images/Poplar%20&%20Willow.pdf

#### 2.2.5.2 Fodder blocks

In many parts of New Zealand, farmers face a severe feed shortage for their livestock during summer due to reduced pasture yield. Drought can limit the livestock production on many pastoral farms especially in the East Coast regions of Gisborne, Hawkes Bay, Wairarapa, Canterburry and North Otago. These regions face severe summer/autumn droughts every seven to ten years and future climatic predictions indicate further severity of droughts on New Zealand's East Coast (Salinger, 2000).

Some varieties of trees and shrubs are well recognised as valuable sources of feed for grazing or browsing livestock during the extreme climatic conditions that limit pasture growth (Sankary & Ranjhan, 1989). In New Zealand, willow trees have been used successfully as a source of fodder for sheep and cattle during summer/autumn feed shortages (Moore et al., 2003). Willow, such as *Salix matsudana* × *alba*, are valuable trees to supplement forage for stock during summer in dry areas (Douglas et al., 1996). Edible forage (leaf and stem material < 5 mm in diameter) yields of 2.6-7.1 t DM $ha^{-1}$ $yr^{-1}$ and 65%

digestibility have been reported for *Salix matsudana* × *alba* (Hathaway, 1986b; Hathaway, 1986c; McCabe & Barry, 1988).

The palatability of willow decreases with increase in tree height due to an increase in condensed tannin concentration, while tree size has no effect on protein concentration (Albrectsen et al., 2004). However, the level of tannin concentration differs between *Salix* species. Oppong (1998) reported higher total tannin concentration for *S. kinuyanagi* (255 g $kg^{-1}$ DM) compared to *S. matsudana* × *alba* (60 g $kg^{-1}$ DM). Although willow are deciduous, they can retain green foliage for 6.5 months that can be utilised during the summer (Plate 2.6) feed shortage (Oppong, 1998). The leaves of *S. kinuyanagi and S. matsudana* × *alba* also retain the recommended level of nitrogen (17 g N $kg^{-1}$ DM) for an adequate diet for a lactating ewe rearing a lamb (Oppong, 1998).

Sheep preferences for *S. kinuyanagi* and *S. matsudana* × *alba* depend on the season (Stace, 1996). The *S. matsudana* × *alba* is preferred for browsing in summer rather than autumn while the reverse is true for *S. kinuyanagi* (Oppong, 1998).

A comprehensive study by McWilliam, (2004) on the effect of willow and poplar supplementation on the reproductive performance of ewes showed that poplar trimmings are beneficial for increasing the reproductive rate of ewes grazing drought pasture during the pre-mating and mating periods. It was also reported that poplar supplementation increased intakes of DM, metabolisable energy (ME) and crude protein (CP). The CT content of poplar was higher at 7 g $kg^{-1}$ DM compared with 1.5 g $kg^{-1}$ DM in pasture. Increased protein absorption due to the CT content enhanced the ewe reproductive rate from poplar supplementation.

Kemp et al., (2001) also reported that poplar and willow tree fodder is superior in nutritive value to typical hill pastures in dry summers. Willow supplementation can also reduce the live weight loss of beef cattle under prolonged drought conditions and can be used as a readily available and low cost drought supplement (Moore et al., 2003).

Plate 2.6 Willow fodder block ready to be grazed during a summer drought period at Massey University's Riverside Farm near Masterton, New Zealand.

### 2.2.6 Willow and poplar-pastoral system in New Zealand

Silvopastoralism aims at the integration of trees, pasture, and grazing herbivores for a combined production benefit that is greater than the value of any component individually. However, the real benefit from silvopastoral practices can only be realized through better understanding of the production requirements of each component (Garrett et al., 2004).

Silvopastoralism is an old practice in Europe (Braziotis & Papanastasis, 1995) but in New Zealand, this form of agroforestry was not formally considered until 1969 (Hawke & Knowles, 1997). *Populus* and *Salix* are commonly planted in silvopastoral arrangements in New Zealand (Stace, 1996). New Zealand is probably the one of the few places in the world where poplar are planted on hillsides (Wilkinson, 1993).

In New Zealand, willow and poplar are planted on pastoral land under two different systems that differ in objectives. Firstly, willow and poplar are planted in hill country at a low density. The purpose of this kind of pastoral system is to control soil erosion and provide shelter to the animals. Secondly, willow and poplar are planted at very high density to create coppice fodder blocks. Such blocks are browsed at a height of 0.3 to 1.3 metres (McWilliam, 2004) a few times annually, especially in summer when drought causes serious shortage of pasture.

In hill country, the wide space planting of willow and poplar suits farm operations. Trees are planted at low densities of 25 to 150 stems $ha^{-1}$ (Wall et al., 1997; Wilkinson, 1999) which have proven sufficient to control soil erosion through rain interception and providing a subsurface root network that helps soil binding and reduce slips. The management of a willow-poplar-pasture system involves protection of individual poles from farm livestock for up to three years using fencing and/ or plastic sleeves to avoid their production potential being compromised (Charlton et al., 2003; Wilkinson, 1999). Sheep, cattle, deer and rabbits tend to damage/ring-bark young trees. The nylon sleeves help prevent such damage while fencing is ideal to reduce damage from mature cattle.

The low density willow and poplar plantings in hill country provide opportunity for farmers to feed their animals at a time of feed shortage. Such a system offers several feeding options. Trees can be mechanically pruned to a desired height and lower branches and foliage can be fed to the animals. Trees between five to ten years can be pollarded beyond the cattle browsing height of 2.0 to 2.5 m (Charlton et al., 2003). Pollarding forms a 'pruning nest' that allows farmers easy access for pruning. Pollarding has the added benefit of reducing shading impact on pasture growth (Douglas et al., 2001). Falling leaves in summer can also be useful feed for farm animals during drought periods. Trees shed leaves prematurely in times of drought to counter rapid transpiration loss through leaves and these leaves provide fodder that is much needed during drought (McGregor et al., 1999). The fresh fallen leaves are palatable compared to the pasture available at that time. Mature poplar trees (> 30 years) planted at low density (37 stems $ha^{-1}$) can produce up to 84 kg DM $tree^{-1}$ equating to 3.1 tonnes DM $ha^{-1}$ of fallen leaves (Guevara-Escobar, 1999). Similarly, Kemp et al., (2001) measured 9.5 kg and 7.5 kg edible DM (leaves + stem ≤ 5 mm) from seven-year-old Tangoio willow *(S. matsudana × alba)* and Veronese poplar *(P. deltoides × nigra)* trees grown on Wairarapa hill country, respectively.

On the other hand, high density (1,500 to 30,000 stems $ha^{-1}$) fodder blocks are planted in areas that are currently underproductive. These fodder blocks are established by planting willow/poplar stakes (1.0 to 1.2 metres in length) (Douglas et al., 2003). Tree establishment and subsequent management require fencing of such blocks for one to two years. Trees are coppiced after one to two years at a height of 0.3 to 1.3 m creating a stump for future shoots.

The fodder blocks are created once and involve some initial cost to set up but offer continuous benefit of rotational grazing several times a year for many years. The maximum biomass production from a coppiced willow system has been measured in the fifth growing season. However, seasonal and annual variations in climatic factors like temperature and rainfall can affect the DM yield in a tree coppice system (Kopp et al., 2001). The fodder from coppiced poplar/willow trees can be harvested by either mechanically pruning the primary growth and foliage or by direct grazing by livestock (Douglas et al., 2003). Direct grazing of such trees is more economical and easy compared to mechanical pruning that is labour intensive and time consuming.

## 2.3 Effect of trees on pasture production

Deciduous tree based silvopastoral systems develop competitive environmental interactions between tree species and the understorey pasture that may have either positive or negative effects on any of the components. Soil moisture, light and soil temperature are the most important factors that determine the performance of either component in such a system. Pasture species respond differently to an increase or decrease in the level of these factors (Devkota, 2000; Guevara-Escobar, 1999). However, it is quite unusual for these environmental factors to be optimal at the same time under natural conditions because optimisation in one factor may affect the other. For example, an increase in light intensity increases the soil temperature and can affect the soil moisture adversely. Similarly shading by trees usually has a negative impact on understorey pasture growth. However, during summer, when light is intense and soil moisture is in short supply, then shade may be advantageous to pasture.

Limited work has been done on tree pasture interactive factors in recent times in New Zealand. Guevara-Escobar (1999), conducted a study involving young (5 yrs old and 50-100 stems $ha^{-1}$) and mature (>29 yrs old and 37-40 stems $ha^{-1}$) poplar trees in hill country pasture and reported that pasture accumulation under mature poplar trees was 40 % of that in the open-pasture and this ratio remained constant despite the higher mean soil water content at the poplar-pasture area. Pasture accumulation under young trees was similar to open-pasture. The lower pasture accumulation under mature trees was attributed to shading and not to the soil moisture and it was suggested that light should be considered as the limiting factor for pasture growth. The results are supported by Ong et al., (1996) who consider light as the primary limitation when water and nutrients are sufficiently available.

Devkota (2000) used a pruning technique to investigate the effect of light and shade on different pasture species in relation to an Alder silvopastoral system in New Zealand. It was reported that pasture species responded differently to light intensity and shade. All grasses and legumes showed a linear increase ($P<0.0001$) with % ambient photosynthetically active radiation (PAR). The highest and lowest shoot dry matter was reported at 70% and 14% PAR, respectively. Shade also affected the tillering ability of pasture species. Herbage mass of swards in heavy and medium shade under the Alder trees was 50% and 70%, respectively, of that of light shade. Cocksfoot either with lotus or white clover gave the highest herbage mass whereas values for perennial ryegrass and Yorkshire fog were reported lower and similar, respectively.

A study by McIvor et al., (2003) at AgResearch's Ballantrae Hill Country Research Station near Woodville, New Zealand, on widely-spaced (8 m × 8 m) poplar, also reported 10-15% less pasture production under trees compared to open-pasture. However, a positive shade effect was observed during late summer and autumn when pasture production under trees exceeded that in open-pasture. A recent study by Kallenbach et al., (2006) also reported a reduction in cumulative forage production (20%) under trees compared to open pasture.

## 2.4 Effect of trees on soil water content

Species, age, size and rooting system are the major tree physical factors that affect the rate of water uptake from the soil. However, climatic factors such as quantity of radiation, and the amount and frequency of rainfall and soil physical properties also determine the ability of trees to use soil water. Teskey & Sheriff (1996) conducted a study on 16 years old *Pinus radiata* in Australia to estimate water use and reported that daily water use was greater for large trees than for small trees.

Guevara-Escober (1999) reported that mature poplar-pasture (>29 yrs old) used more water during November as evapotranspiration (2.7-3.0 mm $day^{-1}$) than open-pasture (2.2 mm $day^{-1}$). Although soil moisture contents were significantly lower in the top soil (0-150 mm) for year 1996 under mature poplar, results varied with sites, aspect and time of the year with one site having lower temperature (up to 3.6 $^{o}$C) and higher soil water content (up to 12.2 % v/v) in spring due to shade. However, no significant differences were found in soil temperature and soil water content between young poplar-pasture (5 yrs old) and open-pasture. McIvor et al., (2003) reported significantly less soil moisture content under poplar at depths below 200 mm during summer while no significant differences were found in the top soil (0-200 mm). Most recent work by Douglas et al., (2006) on 8-11 years old widely spaced poplars showed that trees were not effective in winter whereas during summer, plots beneath trees had 8% lesser soil moisture, suggesting that trees use more water due to higher evapotranspiration when temperature is high and trees have maximum leaves on them.

Roygard (1999) reported different responses between *S. kinuyanagi* and *E. nitens* to water stress, as *S. kinuyanagi* significantly reduced its leaf area by shedding leaves due to higher evapotranspiration while *E. nitens* did not show significant drop in leaf area. The rooting system varies among different species and contributes to difference in water use at different depths in the soil and their response to water stress. Willow has a mat-like shallow rooting system (Roygard, 1999) compared to some Eucalypts that have a deep rooted system and can draw water further than 8 m below the surface (Dye, 1996). That is why willow respond early to water stress by shedding their leaves (Roygard, 1999) as water deficit is more severe in the top layers. Leaf shedding by plants is a common phenomenon in the event of drought induced stress. Plants react to drought to minimise the damage due to rapid dehydration. Drought induced senescence contributes to remobilisation of nutrients, allowing the rest of the plant to benefit from nutrient accumulation (Munne-Bosch & Alegre, 2004).

Water availability is the key to water use by trees (Lindroth & Cienciala, 1996). Teskey & Sherrif (1996) reported that daily transpiration was highly correlated with available soil water in the upper 1 m of soil in a *P. radiata* stand in Australia. Trees exhibit seasonally variable transpiration. During summer, the low rainfall and high temperature cause low water input to the soil and high evapotranspiration rates, respectively. This affects the uptake as the transpiration rate exceeds the water available for uptake by the trees. *S. kinuyanagi* can transpire more (20.5 L day$^{-1}$) compared to *E. saligna* (18.8 L day$^{-1}$) (Roygard, 1999). Similarly, stand level studies have shown that daily water use rates for eucalypts were higher than pines at the same age due to faster growth rates in eucalypts (Myers, 1993; Myers et al., 1996).

Leaf area is also a useful parameter to describe water use by trees. Water uptake by trees increases with an increase in tree leaf area and vice versa. Myers et al., (1996) reported that *E. grandis* used 22% more water than *P. radiata* because the annual mean LAI of the eucalypts was three times greater than that of the pines. This indicates that fast growing species can have a significant effect on soil water use very early compared to slow growing trees.

Similarly, Roygard (1999) reported higher evapotranspiration rates for *E. nitens* than *S. kinuyanagi* due to greater leaf area for the former. This increased the soil water deficit as low as 104 mm and 110 mm for both species, respectively. However, the deciduous nature of willow makes them leafless during winter and thus ineffective to soil water use. Roygard (1999) reported a decrease in ET and rainfall interception under willow resulting in greater winter drainage than evergreen trees.

## 2.5 State of soil erosion in New Zealand hill country

Early European settlers in New Zealand cleared a substantial proportion of land under dense native forest and scrub that later formed the basis for pastoral farming. Land clearance exposed much of the hill country to erosion and this was coupled with rapid discharge of extensive rain water capable of flooding lowland areas. The Regional Catchment Boards were constituted in 1940 to deal with the problem of erosion and flooding and implement strategies that could lead to hillside stabilisation and riverbank protection along with other developmental tasks. This led to the extensive planting of willow and poplar trees (Wilkinson, 1999) in hill country and along riverbanks.

The government decision to subsidise the erosion control schemes enhanced the plantation of trees and Regional Catchment Boards managed to plant two million willow and poplar trees during 1960s and 70s (Wilkinson, 1999). Planting of poplar and willow on unstable pastoral land made it possible for farmers to graze livestock in such areas that were under-productive previously.

Eyles & Newsome (1992) estimated that 33 % (3.75 M ha) of the North Island and 25 % (3.83 M ha) of the South Island require significant soil conservation measures. Over 58 % of the farmland in the Wanganui-Manawatu and Greater Wellington Regional Council areas including the Wairarapa region contains erosion susceptible land (Hicks, 1995) and requires significant conservation measures.

# 2.6 Phosphorus (P)

## 2.6.1 Importance of P and its role in eutrophication

P is an essential element for all forms of life and is one of the most important mineral nutrients in agricultural systems (Hart et al., 2004), especially with regard to storage and transfer of energy through phosphorilation. P supply is necessary for seed and root formation and for synthesis of microbial biomass in ruminant animals (Whitehead, 2000).

In temperate agroforestry systems such as silvopasture, both animal manure and inorganic fertilisers are often used. Nutrient losses depend on their source (organic vs inorganic) as well as the soil type. While there is a risk that P losses from such systems can be high because of high application rates of fertiliser with high P concentration, the loss of P mainly depends on the P retention capacity of the soil. Normally the P loss from soil of high anion storage capacity would be less than the P loss from soil of lesser anion storage capacity. However, exceptions can occur when P is surface applied under conditions that favour excessive surface runoff (Nair et al., 2004).

Eutrophication is the natural aging of lakes or streams brought on by nutrient enrichment. This process can be greatly accelerated by human activities that increase nutrient loading rates to water (Sharpley et al., 2003). The pollution from point sources has been well identified and reduced significantly but the contribution from diffuse agricultural sources of P needs more attention. In most instances, diffuse sources are considered to be the major sources of P loss from agriculture (McColl & Hughes, 1981; Sharpley & Rekolainen, 1997). That is why the subject of P losses from agricultural land has led to a proliferation of research in the last decade or so (Gillingham & Thorrold, 2000; McDowell et al., 2001; Monaghan et al., 2005a; Monaghan et al., 2007).

Agriculturally derived P movement to surface waters has well established connections to eutrophication (Cassell et al., 1998.; Correll, 1998; Gillingham & Thorrold, 2000; Quinn & Stroud, 2002). P is one of the least mobile plant nutrients, yet it can be transferred from agricultural lands to water bodies dissolved in surface runoff, attached to eroded sediment, and to a lesser degree leached through the soil profile. The P in sediment includes P associated with soil particles and organic material eroded during flow events (Sharpley et al., 1992). Surface runoff from grass, trees or non-cultivated soils carries little sediment and is, therefore, generally dominated (about 80 %) by dissolved P (Sharpley, 1995). However, reduced runoff under trees may affect the dilution and runoff generated after fertiliser application or livestock grazing may have higher concentrations of particulate P than dissolved from tree-pastures than treeless pastures. Similarly, in hilly country such as New Zealand where slips and slides are common, most of the runoff is expected to have higher particulate P than dissolved (Smith, 1987). The dissolved form of P comes from the release of P from fertiliser and soil and plant material (Fig 2.1) and is readily available for biological uptake (McDowell & Koopmans, 2006). The sediment P is not readily available for biological uptake but it can be a long-term source of P for aquatic biota (Ekholm, 1994; Sharpley, 1993). According to Schnoor (1996), an increase in P tends to result in nuisance algal bloom.

P loss in runoff is affected by runoff volume, sediment loss, forms and concentration of soil P and depth of mixing of soil and water (Cassell et al., 1998.; Sharpley et al., 1992). The precipitation and soil surface characteristics are also important factors in determining P loss in surface runoff (Gillingham & Gray, 2006). Although significant amounts of P can be lost to water bodies via subsurface pathways, it is reasonably well established that in most watersheds P export occurs mainly in overland flow (Sharpley et al., 1999; Sharpley & Rekolainen, 1997).

Although, most of the P loss from catchments occurs mainly in surface runoff, P can also be transported in drainage waters, especially in soils with artifical subsurface drains (Houlbrooke et al., 2004a; Houlbrooke et al., 2004b; Sharpley et al., 2003). Generally, the concentration of P in water percolating through the soil profile is low because of P fixation by P deficient subsoils. Exceptions occur in sandy, acid organic, or peaty soils with low P fixation or holding capacities and in soils where the preferential flow of water can occur rapidly through macropores and earthworm holes (Bengtsson et al., 1992; Sharpley & Syers, 1979; Sims et al., 1998).

The amounts of P lost per annum in runoff may be inconsequential from an agronomical point of view but only very small concentrations of P are necessary for a body of water to become eutrophic (Hart et al., 2004). According to Redfield's ratio, a single atom of P supports the production of as much phytomass as 16 atoms of N and 106 atoms of C (Tett et al., 1985). Since Redfield’s ratio (C:N:P) applies to marine water and there is no mechanism in freshwater ecosystems that allows for adjustments in the rapid P cycle in order to maintain Redfield's ratio, N and C cycling will respond promptly once P is added (Smil, 2000).

In New Zealand the concentrations of total P (TP) and dissolved reactive P (DRP) in fresh waters that are likely to cause adverse biological effects are 26 to 33 and 9 to 10 µg $PL^{-1}$, respectively (Australia and New Zealand Environment and Conservation Council, 2000). The threshold of DRP for saturation of algal growth is considered to be 15 to 30 µg $PL^{-1}$ in New Zealand (Ministry for the Environment, 2001).

In most soils, the P content of surface horizons is greater than that of the subsoil because of sorption of added P, greater biological activity, cycling of P from roots to aboveground plant biomass, and more organic material in surface layers (Sharpley et al., 2003). Particulate P includes the P sorbed by soil particles and organic matter in runoff. The desorption, dissolution and extraction of P from fertiliser, soil and plant material initiates the transport of dissolved P (DP) in runoff (Sharpley, 1995). The rainfall interaction with the thin layer ((1 to 5 cm) of surface soil initiates this process that leads to runoff (Sharpley, 1985). However, this depth is variable due to variations in the rainfall intensity and vegetative cover and is difficult to quantify precisely.

Transparency and colour are the most obvious indicators of the nutrient condition of a water body: Transparent oligotrophic waters support low plant productivity and appear either blue or brown (when stained in peaty regions); eutrophic waters have high primary productivity as large amounts of phytoplankton make them turbid and limit their transparency to less than 50 cm. Lake Taupo, a reknown tourist attraction in New Zealand, has declining water clarity due to increased phytoplankton levels because of high $NO_3^-$-N levels (Betteridge et al., 2005).

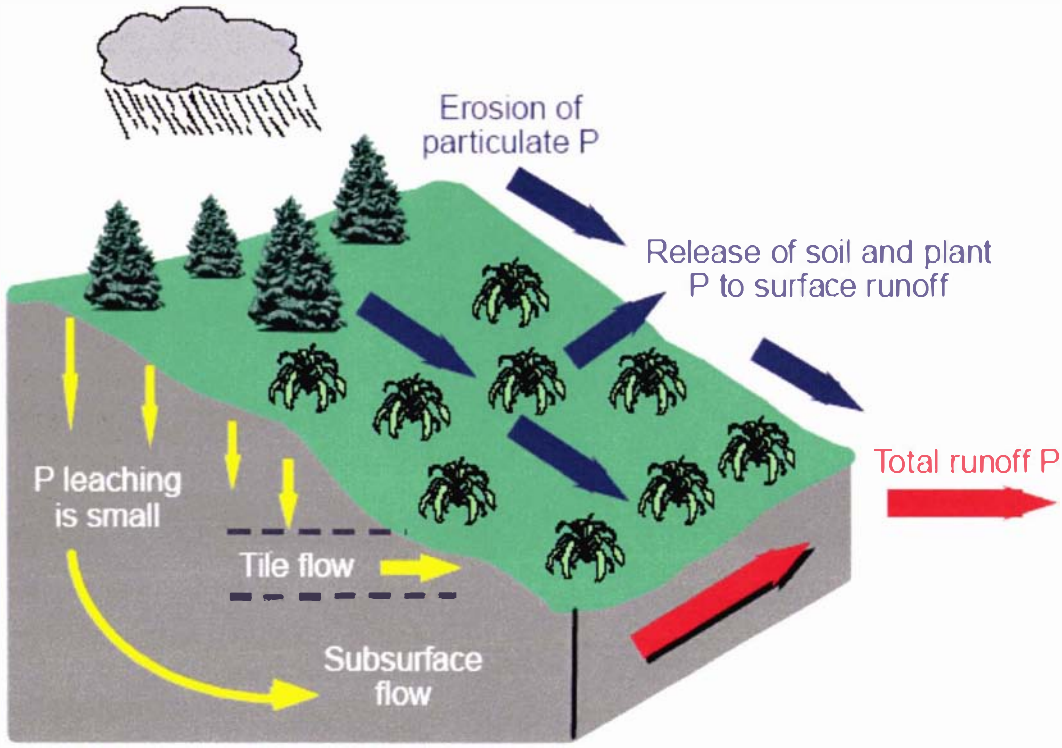


Figure 2.1 P can be released from soil and plant material to surface and subsurface runoff water or lost by erosion.

Adapted from (Sharpley et al., 2003).

Advanced eutrophication is marked by blooms of cyanobacteria (commonly *Anabaena*, *Aphanizomenon*, *Oscillatoria*) and siliceous algae (*Asterionella, Melosira*), scum-forming algae (such as *Phaeocystis pichetii*), and potentially toxic algae such as *Dinophysis* and *Gonyaulux*. Eventual decomposition of this phytomass creates hypoxic or anoxic conditions near the bottom, or throughout a shallow water column (Smil, 2000). P being the growth-limiting element in most fresh water environments, needs to be controlled from entering water resources so that accelerated eutrophication can be reduced (Daniel et al., 1998.; Klatt et al., 2003.).

### 2.6.2 Forms of P in runoff

The various forms of P that exist in runoff water can be divided into two major categories namely organic and inorganic. P from each category can be further divided into two fractions described as particulate and dissolved forms. These forms of P are determined by filtration: a filter size of 0.45 µm is most commonly used to separate the particulate from dissolved form. Since P can occur in a number of sizes down to near-molecular dimensions, the definition of particulate and dissolved forms is arbitrary and, in some ways, a matter of analytical convenience (Haygarth & Sharpley, 2000; Nash et al., 2000).

### 2.6.3 Effect of sheep grazing on P losses

Animal dung, especially when it is fresh, contains concentrations of P that can increase the P concentration of runoff water to undesirable levels. McDowell & Stewart (2005) determined the P fractions in fresh and air dry dung of animals using sequential fraction and P-31 nuclear magnetic resonance (NMR) spectroscopy. They found that sheep dung was richest in P (8 g $kg^{-1}$) compared to cattle dung (5.5 g $kg^{-1}$). Most P in fresh dung was extractable by water (15-36 %) and bicarbonate (36-45 %) but the P shifted to recalcitrant, HCL (12-28 %) and residual P forms (15-31 %) with drying. Only 15 % P was reported as organic in the dung and this small organic concentration was related to low phytate content in pasture. It was concluded that sheep and cattle dung bioavailability decreases with drying thereby affecting the potential for runoff. Shand et al., (2005) also confirmed that sheep dung was dominated by inorganic orthophosphate with minor amounts of organic P.

Grazing causes large increases of nutrients and organic matter in runoff. Elliott & Carlson (2004) investigated the effect of sheep grazing on sediment and nutrient loads from a hill pasture in the Waikato region of New Zealand. They found that Intensive sheep grazing followed by high rainfall increased sediment load, DRP and dissolved organic P by factors (times) of 13-16, 33-76 and 5-7, respectively. Soil erodibility in winter was reported to be double that of summer. Notably, small rain simulators were used for the first time to assess the effect of sheep grazing on nutrient loss in an experiment in New Zealand.

Williams & Haynes (1992) constructed a balance sheet for P, S and K for a long-term trial (38 years) on border-strip irrigated land supplied with superphosphate fertiliser and grazed with sheep. It was reported that of the nutrients applied with fertiliser, 51-59 % of P and 15-30 % of S were retained in the soil. Major losses of P were attributed to runoff and leaching. It was further reported that major concentrations of P and S were in the areas where sheep camping occurred.

### 2.6.4 Effect of superphospate fertiliser application on P losses

The global use of phosphate fertilisers increased over the last century (Bennett et al., 2001; Maene, 2001). A recent review by Macleod & Moller (2006) indicates that in New Zealand, the indices of intensification involve increased inputs to agroecosystem (especially fertilisers and water). The effect of P enrichment on waterways and lakes have caused serious concern to resource managers (Gillingham & Thorrold, 2000).

It was once thought that P was completely immobile in soil, and thus farmers could be encouraged to increase phosphate fertiliser application without fear that P applied in excess of crop requirements would be lost from the soil profile (Haygarth & Jarvis, 1999). However, it is now known that P accumulated in soils or freshly applied in fertiliser may be lost from soil through leaching and surface runoff (McDowell et al., 2004; McDowell & Condron, 2004). New Zealand pastoral farm land is intensively grazed and receives predominantly single superphosphate fertiliser. Although the application of P fertiliser is aimed at maintaining soil P levels but its loss from surface runoff and drainage (to some extent) from pastoral lands can alter the concentrations to an undesirable level (Correll, 1998; McDowell et al., 2004).

It has been reported that water-extractable DRP levels in soils have a direct bearing on DRP concentrations in both overland flow and subsurface drainage (McDowell & Condron, 2004). Davis et al., (2005) investigated the relationship between DRP in runoff and soil P for three different types of soil. The authors found highly significant relationships ($P < 0.001$) between runoff DRP and soil water soluble P (WSP) for the individual soil series ($r^2 > 0.88$). Highly significant relationships ($P < 0.001$) also existed between DRP in runoff and different P saturation indexes for the soil. This indicated that the relationships were soil specific and P management decisions should consider soil characteristics.

McColl & Gibson (1979) reported that superphosphate application resulted in large increases in P concentration in runoff from a previously grazed pasture. However, little effect on P concentration was observed when superphosphate was applied to long grass. It was noted that under long grass, fertiliser movement was prevented by both a reduction in water movement and enhanced adsorption by soil and vegetation.

Austin et al., (1996) determined the relationship between single superphosphate application rate and runoff P concentration by applying four different fertiliser rates (250, 500, 750, and 1000 kg $ha^{-1}$) to twelve 30 m × 8 m flood irrigated bays in Victoria, Australia. Total P (TP) and filterable reactive P (FRP) concentrations in runoff increased linearly with application rate. It was also noted that concentrations were significantly higher in initial runoff volumes ($p < 0.025$) than those in later events. The primary mechanism for the movement of P in runoff following single superphosphate application was through dissolution, rather than sediment transport.

# 2.7 Nitrogen (N)

## 2.7.1 Importance of nitrogen and its role in eutrophication

Nitrogen is present in the environment in many forms. The predominant form is nitrogen gas ($N_2$). Nevertheless, $N_2$ is almost inert and cannot be used directly by most organisms since a substantial amount of energy is required to split the $N_2$ triple bond ($N \equiv N$). Nitrate and ammonia are the two forms used by plants. Organic N is mineralized by microorganisms to create these two forms that are found in our soil and water.

Eutrophication is also largely driven by transportation of N from natural and anthropogenic sources (Cole et al., 2006). The N comes from a variety of sources, including runoff from agricultural fields, concentrated animal feeding operations, atmospheric deposition from fossil fuel combustion, and sewage and septic wastes (Howarth, 2005). In most estuaries, N limits primary productivity. However, if present in excess, it can lead to eutrophic conditions, which can adversely affect water and habitat quality. In freshwater systems, N along with P serves as the limiting nutrient. The level of N determines the biological productivity of the lake, pond, or stream. A sharp increase in the concentration of N can result in an algal bloom. Other effects of eutrophication include loss of species diversity (loss of fishery), increases in water turbidity, and hypolimnetic loss of dissolved oxygen (anoxic conditions) for thermally stratified eutrophic reservoirs due to the oxidation of organic matter by microbes, which exerts oxygen demand (Mason, 1996).The increased vegetation may impede water flow and navigation and the decaying algae often causes taste and odour problems (Mason, 1996).

Soil environmental factors such as soil moisture and temperature control the release of N from organic N sources. The increase in soil moisture and temperature increase the net release of N depending on the organic source (Agehara & Warncke, 2005). Mineral forms of N do not bond as readily to soil minerals or organic matter as does P.

The ratio of TN to TP is often used to define the limiting nutrient. P is considered the limiting nutrient when TN:TP is greater than 17 whereas N is the limiting nutrient when TN:TP is less than or equal to 10 (Smith, 1982). For TN:TP between 10 and 17, P and N are co-limiting nutrients. P is not needed for algal growth in such large amounts as carbon, oxygen, hydrogen, or nitrogen. Nitrate ($NO_3^-$-N) and ammonium ($NH_4^+$-N) are common inorganic N forms found in natural waters. The $NH_4^+$-N is the preferred form of N for plant growth since the reduction of $NO_3^-$-N to the amino group (-$NH_2$) requires additional energy. Nevertheless, the amount of $NH_4^+$-N in the aquatic system is usually less than $NO_3^-$-N since unlike $NH_4^+$-N, $NO_3^-$-N moves easily through soils.

### 2.7.2 Effect of sheep grazing on nitrogen losses

Cattle (60 %), and sheep (12 %) produce the most animal manure N at a global scale (Oenema & Tamminga, 2005). Faeces contain N predominately in the organic form, while 60-70 % of cow urine N and 70-80 % of sheep urine N is in the form of urea (Bellows, 2001). Urine can pass through the soil macropores quickly and increase the $NH_4^+$-N concentration in the soil solution due to extremely rapid hydrolysis of urine-urea (Haynes & Williams, 1992). Cows deposit a higher rate of urine (10 L $m^{-2}$) compared to sheep (5 L $m^{-2}$) (Saggar et al., 1988b). This indicates that under dairy conditions, macropore flow of urine, and the subsequent increase in the N concentration of drainage, is more likely than with sheep grazing. Efficiency of N use by animals can be increased by diet manipulation. Grazing sheep and cattle on grasses high in water soluble carbohydrate results in less N excretion in urine (Freney, 2005).

Elliott & Carlson (2004) reported that sheep grazing in hill country increased concentrations of N in overland flow by factors of 33-76 and 5-7 for ammonium-N and dissolved organic-N, respectively. Caution was advised for winter grazing under New Zealand conditions. Powell et al., (1998) determined the effect of urine on soil chemical properties and reported that an average voiding of sheep urine to a sandy, siliceous soil increased soil pH and ammonium levels dramatically in the upper 10 -15 cm of soil, especially during the first week following application.

In hill country, some areas of pasture (e.g. beneath trees, around gateways, and on ridges and hill crests) can have greater N loadings and potential for leaching, or losses via runoff, due to strong camping behaviour of the sheep. Saggar et al., (1988a) reported that 60 % of the dung and 55 % of the urine are deposited on campsite areas that occupy 15-31 % of the land area.

Nitrate leaching losses are generally lower in sheep-grazed pastures than for cattle because sheep have a smaller bladder and urinate more often in smaller volumes (Morton et al., 1993). Magesan et al., (1996) reported that periodically mob-grazing by sheep on flat land had no measurable effect on the nitrate concentrations in the drainage collected during or immediately after grazing.

### 2.7.3 Effect of nitrogen fertiliser application on N losses

Human activities, especially agricultural activities, have approximately doubled the rate of N input into the terrestrial N cycle and this rate is still increasing (Smith et al., 1999; Vitousek et al., 1997). There is widespread concern that N and P originating from agricultural land is causing contamination of ground and surface waters leading to nutrient enrichment of New Zealand lake systems (Cullen et al., 2006; Dooley et al., 2005) of great tourism and cultural values (Carr, 2005; Hall & Stoffels, 2005). The detection of the *Cylindrospermmosis raciborskii* planktonic freshwater cyanobacterium in lake Waahi (Waikato) has raised concern in recreational, stock drinking and potable water supplies in New Zealand (Wood & Stirling, 2003). Nitrate leaching is the major cause of N loss from agricultural systems and the amount of N in surface runoff is strongly influenced by a combination of land use and management practices (Hamilton, 2004), soil types and climatic conditions.

In winter, up to 30 % of the N applied in fertiliser may be leached. This will result in a relatively low pasture growth response to the added N. However, application of N fertiliser in autumn results in larger pasture responses to N, which can be carried through for winter grazing, and minimises direct leaching of fertiliser N (Ledgard et al., 1988).

In New Zealand, relatively low amounts of fertiliser N are used on sheep farms (e.g. 20 kg N $ha^{-1}$ $yr^{-1}$) (Morton et al., 1993). Magesan et al., (1996) measured nitrate-N in the drainage from two hydrologically similar mole-and pipe drained paddocks over three years near Palmerston North, New Zealand, and reported that the application of urea (50 Kg $ha^{-1}$) in early spring had no significant increase on the $NO_3^-$-N concentrations in the drainage water.

In general terms, as the application of N to pasture increases, N losses increase. Whilst the soil can act as an N sink by immobilising or absorbing N, increasing amounts are lost as $NO_3^-$-N in drainage. Monaghan et al., (2005a) conducted research on the effect of increasing N on nitrate-N losses near Edendale township in eastern Southland, New Zealand. Treatments were established on hydrologically-isolated replicate plots (900 $m^2$) where pastures received annual fertiliser N inputs of 0, 100, 200 or 400 kg $ha^{-1}$ and were grazed throughout spring, summer, and autumn of each year by non-lactating dairy cattle. Significantly increased losses of nitrate-N in drainage were reported as the application rate increased. Considered from the perspective of promoting nuisance weed and algal growth in surface waters,, losses of N in drainage water under the greater application rates exceeded accepted guidelines for N. It was suggested that annual fertiliser N inputs should not exceed approximately 170 kg N $ha^{-1}$ $yr^{-1}$.

## 2.8 Effect of landuse on sediment and nutrients losses

The exact amount of N and P lost from agricultural systems varies dramatically depending on the landuse type (e.g. sheep or dairy versus forestry) and management practices (Monaghan et al., 2007). Changes in landuse or management practices may affect water outflow, sediment and nutrients losses (Chaplot et al., 2004). Trees planted at spacings of 12 metres or closer have been reported to reduce mass movement (slipping) of soil under pasture by 50 to 80% in hill country (Hicks, 1995).

Several studies have been conducted in New Zealand and overseas involving trees in forested catchments, riparian strips and shelter belts to investigate overland flow, sediment and nutrient losses. McColl et al., (1977) conducted a catchment-scale study between forest (native and exotic) and hill pasture in Taita, New Zealand. P and N losses were measured in stream runoff. Significantly greater losses of TP and DRP were reported from pastoral catchments compared to forested ones. The estimated TP losses from pasture were reported to be 292 g $ha^{-1}$ $y^{-1}$ compared to values of 201 g $ha^{-1}$ $y^{-1}$ and 124 g $ha^{-1}$ $y^{-1}$ from native and exotic forest catchments, respectively. Large differences in $NO_3^-$-N losses were also reported between hill pasture catchments and forested catchments. Hill pasture sites lost about 1400 g $ha^{-1}$ $y^{-1}$ but native and exotic trees catchments lost about 160 g $ha^{-1}$ $y^{-1}$. It is important to note that the pasture catchments did not receive nitrogenous fertilisers. Most of the $NO_3^-$-N runoff occurred in large floods and relatively little $NO_3^-$-N losses were reported at low flows. A positive correlation was reported between concentration and flow rates.

Smith (1987) reported sediment loads and nutrient losses in surface runoff from pastoral catchments at Tauwhare, near Hamilton, New Zealand. Uneven spatial runoff patterns were observed over the period of twenty months where eight individual 1.5 - 2.4 m long collectors intercepted 4 - 333 $m^3$ of runoff water. The differences were attributed to extreme channelisation from both catchements. The mean flow weighted runoff concentrations were reported for total TP, Kjeldahl nitrogen (TKN), $NO_3^-$-N and suspended solids (SS) at 1053 mg $m^{-3}$, 5898 mg $m^{-3}$, 69 mg $m^{-3}$ and 472 mg $m^{-3}$, respectively. Virtually all P and N was transported downslope in winter and spring.

Cooper et al., (1987) monitored streams draining from three catchments under different land uses (pasture, pine and native forest) for 14 years in central North Island, New Zealand. It was reported that in the early years tree catchments had water chemistry similar to pasture alone but differences began to appear after about 4 to 5 years of tree growth and after 7 years of tree growth, water chemistry differences between catchments were apparent every year.

Cooper and Thomsen (1988) conducted a comparative study between forested and non-forested catchments in the North Island, New Zealand. Nutrient (N & P) concentrations were measured in stream water. It was reported that total N export coefficients (kg $km^{-2}$ $yr^{-1}$) were highest in the pasture catchment (1195) followed by native (367) and pine forest (131), respectively. Total P export coefficients were estimated as 167, 9.5, and 12.0 kg $km^{-2}$ $yr^{-1}$ for the pasture, pine, and native catchments, respectively. The stream flow characteristics differed markedly between catchments, with highest total water yield and storm flow yields occurring in the pasture catchment.

Quinn & Stroud (2002) compared sediment and nutrient loads in streams draining from sheep and cattle grazed catchments with pasture, pine plantation and native forest in Waikato hill country, New Zealand. All results were reported in units of kg $ha^{-1}$ $yr^{-1}$. Exports of sediment, $NO_3^-$-N, $NH_4^+$-N and TP from pasture were 2.5-to 7-fold higher than native forest. In contrast, export of DRP was within 20 % of the native stream's values. In general, high water clarity and lower temperature were reported in streams under native forest compared to those in both pasture and pine catchments. Considerable variation, between seasons, and years, in average seasonal discharge and exports of sediment and nutrients were also noted.

Chapman et al., (1999) investigated and compared the N composition of streams draining three moorland and three plantation forest catchments in mid-Wales. Samples of stream water collected over a period of one year were analysed for $NO_3^-$-N and $NH_4^+$-N. Nitrate concentrations were significantly larger in the forested streams. Nitrate also displayed contrasting seasonal patterns being largest in the winter. The results confirm conclusions from other studies that afforestation of upland semi-natural vegetation can promote nitrification within the soil system. Authors emphasized that both inorganic and organic forms of N must be considered in studies that assess the impact of land management strategies on N cycling in terrestrial and aquatic ecosystems.

Riparian buffer strips can intercept surface runoff and act as a filter for sediment and associated nutrients entering the stream. Smith (1992) showed that a 25-35 m wide strip of *Pinus radiata* reduced runoff by 21-55 %. Schoonover et al., (2005) conducted a field scale study involving forest riparian buffer zones to attenuate nutrients in agricultural surface runoff from natural precipitation events. The forest buffer significantly reduced the quantities of incoming dissolved nitrate-N, dissolved ammonium-N, total ammonium-N, and total orthophosphate in surface runoff by 97%, 74%, 68%, and 78 %, respectively within the 10.0 m riparian buffer.

Conversely, Smith (1992) has expressed concerns that although riparian afforestation within pasture catchments can significantly reduce runoff, sediment yield and N and P concentrations and loads may actually increase due to reduced under storey pasture cover resulting in enhanced riparian zone and stream channel erosion. However, this can be partly addressed by avoiding dense plantation of trees to minimise the effect of canopy closure and shading of under storey pasture.

Another concern is that the effectiveness of buffer strips in removing the majority of P from runoff may also decline with time. Cooper et al., (1995) showed that 20 years after retirement of a riparian buffer strip from grazing, P had accumulated to the extent that outflows of dissolved P were matching the trapping of inflowing, sediment-bound P. This effect would be expected to occur in many riparian strips unless their P storage ability was periodically recharged in some manner. In addition, as mentioned above, there is the risk that surface runoff can become channelised, thus overwhelming buffer strips and negating their filtration effect.

Trees improve the infiltration rate of the soil very quickly thereby reducing the quantity of surface runoff. Carroll et al., (2004) studied the effect of shelter belts with young trees of different age groups (2, 6 and 7 years) and reported that water infiltration was 60 times greater under young trees compared to nearby pasture grazed with sheep. The infiltration rate for the 2-years old shelterbelt was markedly greater to that of the grazed areas suggesting that changes in the soil happen quickly. The infiltration rate increased further when going from areas under the 2 to 6 year old trees. However, there was little difference between areas where the trees were 6 or 7 years old.

Nair and Kalmbacher (2005) monitored and compared N and P concentrations within soil profiles between pasture alone and tree pasture (silvopasture). P concentrations were reported in the order: pasture > silvopasture. Ammonium-N and $NO_3^-$-N concentrations were higher in the surface horizon of the treeless pasture. Narain et al., (1998) investigated erosion losses in a field experiment with *Leucaena leucocephala* and *Eucalyptus* in the western Himalayan valley region of India. Trees reduced the runoff and soil loss by 40 % and 48 %, respectively, over maize plots.

## 2.9 Effect of treading on soil properties, runoff and drainage

Often, soil compaction is measured by soil bulk density. On moist soils, the bulk density of the surface layer increases under compaction until the bearing capacity equals the hoof pressure (Wind & Schothorst, 1964). Several authors have reported an increase in bulk density resulting from increased treading intensity (Greenwood et al., 1997; Kelly, 1985; Willatt & Pullar, 1983).

At around field capacity, the soil is more likely to be compacted by treading (Horne & Singleton, 1997). During wet conditions, most of the water is conducted in the soil through macropores. By reducing the volume of macropores, treading often decreases the infiltration rate (Elliott & Carlson, 2004) and percolation and increases runoff and encourages erosion. (Greenwood & McNamara, 1992; Nguyen et al., 1998) have observed that a reduction in soil macropore space by treading led to considerable damage on badly drained fields. Compaction and impeded drainage due to treading can also cause a reduction (70-90%) in earthworm populations (Cluzeau et al., 1992). The vulnerability of earthworms to treading is greater during rainy or wet season because earthworms tend to remain near the soil surface (Lisa et al., 1997). In their review, Gifford & Hawkins (1978) showed considerable evidence of reduction in infiltration caused by treading.

Drewry & Paton (2005) conducted a detailed study on the effects of intensive sheep treading during winter on soil physical properties for 3 years on a newly sown ryegrass-white clover pasture in Southland. Sheep numbers varied from 0, 900 and 1800 ha$^{-1}$. Intensive winter treading caused considerable visual soil pugging and pasture damage. Macroporosity (percentage of pores > 30 μm) at 0–5 cm was significantly reduced from 11.1% in the control to 10.2% and 9.4% in the 900 and 1800 sheep ha$^{-1}$ treatments, respectively. It was also reported that winter treading reduced soil earthworm numbers at the 0-5 cm depth. However, soil macroporosity in the 0-5 cm depth improverd from 9.4 % to 11.3 % in the summer periods.

In another experiment, Drewry et al., (1999) examined the extent of damage to soil physical properties of a Pukemutu silt loam (Pallic Soil) caused by intensive winter grazing at 1800 sheep $ha^{-1}$. Soil structural damage was reported. Significant reduction in soil macroporosity (from 16.4 % to 12.1 %) in the 0-5 cm soil depth occurred. Soil pores were water-filled leading to plastic deformation rather than compaction. Monaghan et al., (2005b) reported a consistent deterioration in surface soil physical condition between early spring and early summer due to cattle grazing in a wet spring in Waikato, New Zealand. During August-December, a period that coincided with grazing, soil compaction as a measure of bulk density, increased. However, conditions improved over late summer, autumn and winter because of no grazing and pasture growth. The soil compaction as a result of treading is greater for cows than sheep. For example, a survey report of 97 sheep and 87 dairy farms in Southland and south Otago by Drewry et al., (2000) showed that air permeability, saturated hydraulic conductivity and macroporosity significantly decreased on dairy farms than sheep farms. Moreover, soil bulk density increased greatly in dairy farms when compared with sheep farms. Positive correlations between increased bulk density and decreased hydraulic conductivity have also been reported by Lisa et al., (1997).

Soil compaction associated with treading increases soil strength (Lisa et al., 1997). This increased soil strength may cause hard-setting of soil that, in turn, restricts water movement (Mullins et al., 1992). Repeated treading in the presence of free water can cause a progressive loss of soil strength (Scholefield & Hall, 1985). Nevertheless, important natural regenerative processes including wetting and drying cycles, which cause shrinkage and swelling and cracking of the soil (Cluzeau et al., 1992) may help repair soil structure.

Excessive top soil and contaminant runoff to waterways can occur due to treading. Foster et al., (1990) observed an increase in erosion rates from grassland to river channels due to treading when grazed at high stocking densities. Runoff volumes can increase up to twelve times in heavily grazed grasslands (Heathwaite et al., 1990). Grazing of pastures on wet soils can develop more potential for water erosion, especially hill country (Betteridge et al., 1999). The increasing numbers of animals grazing the land, especially sheep, can lead to the initiation and erosion of bare soil in the uplands and to trampling and puddling of soils in lowland pastures thereby increasing runoff and sedimentation of water courses (Evans, 2005).

Nutrient movement along with soil particles increases with animal treading from grasslands. Lambert & Clarke (1985) observed greater losses of N and P from catchments in hill pasture under rotational cattle grazing due to greater soil erosion than under rotational sheep grazing. However, pugging can reduce sediment loss because of hoof indentations acting as traps for moving sediments (Russell et al., 2001). Sheep treading can cause a reduction in the N concentration in the soil at high stocking rates either due to increased nitrate leaching and/or surface runoff (Curll & Wilkins, 1983). A 50 % increase in the amount of dissolved inorganic P in tile drainage after four weeks of cattle grazing has also been reported due to cattle treading effects (Sharpley & Syers, 1979). Therefore, greater movement of nutrients due to the treading effect may cause contamination of waterways of New Zealand (Smith et al., 1993).

## 2.10 Conclusions

Willow and poplar are fast growing trees that can be established with great ease in a silvopastoral system with a variety of arrangements under New Zealand environmental conditions. They can survive the grazing pressure during early establishment. However, soil physical characteristics and environmental conditions also play a vital role in establishment and survival of any particular species. The role of these trees in soil conservation is well recognised. Many parts of New Zealand regularly face severe droughts during late summer and early autumn creating forage shortage for livestock. Willow and poplar can offset this feed shortage with better quality lush fodder than drought pasture.

Pasture quantity and quality are often compromised under trees. However, the extent of reduction in pasture growth varies with the nature of the tree species (evergreen green vs deciduous), tree stocking rates, age of the trees and crown form. Silvicultural and management practices can help reduce some of the losses in pasture production.

The potential for animals to cause soil compaction increases with soil moisture content, the weight of the animal being grazed, the number of animals in the paddock, and the amount of time animals stay in the paddock. Animal treading damage should be minimised so that the risk of increased sediment in runoff and increased N and P in waterways is reduced. This could be achieved by winter and spring grazing management strategies that incorporate a stand-off pad (in a non-critical area) to restrict grazing-time on pasture.

Due to its hilly nature, parts of New Zealand are scarred by soil erosion. Sediment and nutrient (N & P) losses from livestock farms are of great concern. The water quality of many rivers and lakes is deteriorating. This deterioration in the quality of the aquatic environment may affect New Zealand's agricultural export and tourism industry.

The exact amount of N and P lost from agricultural systems varies dramatically depending on the land use type (e.g. sheep and dairy versus forestry) and management practices. Research has shown that tree pasture systems have significantly smaller N and P losses than those from treeless pasture. Thus the eutrophic consequences of livestock farming can be addressed, at least partially, through fast growing tree species like willow and poplar that can help utilise soil nutrients, reduce soil and nutrient losses through surface runoff and drainage. Nonetheless, there is little information on the effects of young willow and poplar (< 5 years) on the quality of the aquatic environment in New Zealand. This review clearly points out the lack of information and emphasises the need to quantify the environmental effects of young willow and poplar in silvopastoral system in New Zealand.

The reviewed literature clearly points out the attributes of a silvopastoral system that can help reduce surface runoff, nutrient (N & P) and sediment loss. These attributes are rainfall interception, greater use of soil water, improved soil intactness and improved physical properties of the soil, but understorey pasture may be decreased under such a system in comparison with an open pasture system. However, lack of data on densely planted young trees signals the need for testing the hypothesis mentioned in Chapter 1 (Section1.1) through experimental findings under New Zealand conditions.

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# ESTABLISHMENT OF DENSELY PLANTED WILLOW AND POPLAR AND THEIR EFFECT ON UNDERSTOREY PASTURE GROWTH

## Table of contents

## 3.1 Introduction

In New Zealand, willow and poplar have been planted as wide-spaced trees mainly for soil conservation with considerable success (Wilkinson, 1999). These trees have also been used as shelterbelts or windbreaks for protection of newly developed subtropical fruit orchards, especially Kiwifruit (Van Kraayenoord, 1984). The main reasons for planting *Populus* and *Salix* species have been their fast growth, extensive rooting system, desirable crown shapes and easy establishment. Willow and poplar field plantations can be established with rooted and unrooted stock. Shelter belt plantings are mainly established using rooted stock while most soil conservation, fodder block and river control plantings are established with unrooted poles and stakes (Douglas et al., 2003; Van Kraayenoord, 1984).

The main objective of most silvopastoral systems is to increase, or at least sustain over the long-term, the existing productive capacity of the land through efficient utilisation of, and/or greater conservation of, available resources (Wojtkowski, 1998). The mixing of trees with understorey pasture can enhance the stability of the environment but can impose different demands on the system's available resources on an interspecies basis (Sinclair et al., 2000). Competition for light, moisture and nutrients between trees and pasture plants influence the pasture yield in silvopastoral systems. The level of shade and its duration are among the most significant factors responsible for variation in the pasture growth under trees (Dodd et al., 2005).

The effect of widely-spaced, poplar on pasture production has received some attention during the last decade in New Zealand (Douglas et al., 2006; Douglas et al., 2001; Guevara-Escobar, 1999; Wall, 2006). Similarly, willow and poplar edible dry matter production and nutritive value (Charlton et al., 2003; Douglas et al., 2003; Kemp et al., 2001) and their effects on sheep live weight and reproduction have recently been researched (McWilliam, 2004). However, there has been no comparative study of willow and poplar establishment and relative growth under similar climatic conditions. There is a general perception among researchers that very young willow and poplar (< 2 yrs) may not have any effect on soil water content, and also, may not impose shade that adversely affects the understorey pasture growth. Knowledge of the effect of young willow and poplar (< 2 years) on pasture production is lacking in New Zealand. Therefore, the objectives of this experiment were to:

1 Study the differences in establishment and growth between willow and poplar under similar climatic conditions.
2 Measure the effects of very young willow and poplar on soil moisture.
3 Measure the effect of young trees on understorey pasture growth.

## 3.2 Materials and methods

### 3.2.1 Site description

The site is situated at 'Moginie Pasture and Crop Research Unit' near Massey University, Palmerston North. The slope at the site ranges from 5.8-7.8 %. The site has been managed as permanent pasture during the last decade and has been grazed with sheep on a rotational basis (M. Osborne, technician Massey University, personal communication). The soil type is Tokomaru silt loam. Characteristics of the soil are described in section 5.2.1.

### 3.2.2 Experimental design and treatments

The experiment design was randomised complete block (RCB) with three blocks and three treatments. The trial was established on 8$^{th}$ of October 2004 by planting unrooted willow and poplar stakes. Pasture alone was used as the control. Willow stakes were prepared from branches removed from (*Salix matsudana* × *alba* 'Tangoio') trees near Massey University Palmerston North, while the poplar (*P. deltoides X P. nigra* 'Dudley') stakes were procured from HortResearch Nursery at Aokautere, near Palmerston North. The stakes were 50 cm in length with varying diameters. Each stake was driven 30 cm into the soil, leaving 20 cm above ground. Plots were marked using string. Stakes were planted at 1.2 m spacing in six rows with ten stakes in each row, giving a total of sixty stems in each plot (Plate 3.1a). The site was closed to all grazing animals through out the period of trial. Plots were mowed fortnightly in spring and early summer to reduce the competition for soil moisture and minimise pasture shade on newly sprouting and growing willow and poplar stakes (plate 3.1b). The mowing continued for the rest of study period as deemed necessary. The trial lasted for two years.

### 3.2.3 Tree measurements

Small end diameter measurements were made for all stakes after planting in the field. Subsequent measurements of stem diameter (at ground level), height and number of shoots were made in the winters of 2005 and 2006 to determine the annual growth difference between willow and poplar. However, the winter 2006 measurements also included the canopy diameter for each tree at the maximum canopy spread. Tree stem diameters (mm) were measured using digital vernier callipers. The heights (m) and canopy diameters (cm) of the trees were measured using a survey staff rod and diameter tape respectively.

The canopy closure was estimated from the mean canopy diameter. The measurement of canopy diameter for each tree allowed the measurement of horizontal cross-sectional area of tree crowns ($m^2$ $tree^{-1}$). Since trees were planted on a square grid basis (1.2 × 1.2 m spacing) and the tree canopies were not overlapping, the canopy closure estimation and calculation were based on four nuclei trees using the concept of Wall (2006). The area under the canopy of a single tree within the square grid of four nuclei trees was assumed to be 1/4$^{th}$ of the total area of the canopy per tree (Figure 3.1). Since mean canopy diameter was used, the total area covered within the square of four nuclei trees was to be equal to the total canopy cross-sectional area of a single tree. Thus knowing the cross-sectional area of the circle (mean canopy) of willow and poplar trees, it was possible to calculate the total area covered under the canopies of four nuclei trees within the square grid (1.2 × 1.2 m) at which trees were planted.

Assuming the canopy is circular; a circular cross-sectional area for each tree was calculated using the basic geometric formula:

Area of circle (A) $= \pi r^2$ ------------------------(1)

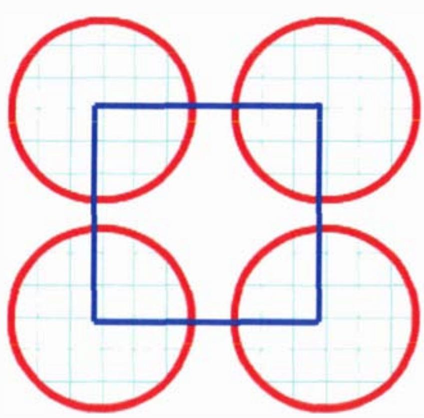

Figure 3.1 The canopies of four nuclei trees (red circles) planted as a square grid (1.2 ×1.2 m spacing). The square with blue lines indicates the actual spacing at which trees were planted while the areas of red circles inside the square show the canopy.

## 3.2.4 Soil sampling and laboratory analyses

### 3.2.4.1 Olsen P

Soil samples were collected using a soil auger from four randomly selected positions in each plot on 11th of October 2004. Samples were collected at two depths (0-75 mm and 75-150 mm). Samples were air dried at room temperature, ground manually and sieved through < 2 mm size sieve before they were analysed for Olsen P and pH at the 'Fertiliser and Lime Research Centre' Massey University, Palmerston North. Olsen P was determined using the method of Olsen et al., (1954).

(a) (b)

Plate 3.1 (a) A view of the experimental site with willow and poplar stakes planted at Moginie, Manawatu. (b) Early sprouting and growth (December, 2004) of willow and poplar at Moginie, Manawatu.

The method involved accurately weighing 1 g of air-dried soil (< 2 mm sieved) into a 50 ml polypropylene centrifuge tube, then adding 20 ml of 0.5 M $NaHCO_3$ solution. Samples were shaken for 30 minutes, in an end-over-end shaker, followed by centrifuging at 8000 rpm for one minute, and filtration through Whatman No. 41 filter papers. Inorganic P was then determined following the phosphomolybdate method of Murphy & Riley (1962).

### 3.2.4.2 Soil bulk density

To determine the soil bulk density, soil samples were collected on 25th of October 2004. Samples were collected only from the open pasture (OP) plots to avoid any damage to the newly planted willow and poplar stakes. Two pits were excavated in each plot with a spade and samples were collected in thin-walled cylindrical aluminium samplers (50 mm dia and 50 mm length) from 0-75, 75-150, 150-225, 225-300, 300-375 and 375-450 mm depths in each pit. Back in the laboratory, each sample was weighed wet and then oven dried at 105 $^{0}$C overnight and then reweighed. Soil bulk density was calculated as described by McLaren & Cameron (1996).

### 3.2.5 Soil moisture measurement

The change in soil moisture at different depths in all treatments was monitored using Time Domain Reflectometry equipment (TDR, Soil Equipment Corp., Santa Barbara, CA). The TDR equipment was calibrated for accuracy against gravimetric soil water content calculated from soil samples used to calculate bulk density (section 3.2.4.2). Permanent TDR probes of 150, 300, and 450 mm length were vertically inserted in each plot of all three treatments. One set of probes was inserted in the middle of each plot at 250 mm distance from a tree. Measurements were made fortnightly except when the TDR machine was out of order or during summer when measurements were intensified to a weekly basis. The soil moisture content for the 150-300 mm and 300-450 mm soil depths were obtained using equation (2) (Guevara-Escobar, 1999).

$$\theta_{zii-zi} = \frac{(\theta_{zii} \times \omega_{zii}) - (\theta_{zi} \times \omega_{zi})}{\omega_{zii-zi}} \text{ --------------------(2)}$$

Where $\theta$ represents the soil volumetric water content and $\omega$ is the total soil volume at the z stratum to depth ii and i, given i < ii.

### 3.2.6 Pasture dry matter sampling

Pasture net herbage accumulation (NHA) rate was measured monthly (July and August were combined) using the trim technique (Radcliffe, 1974) from April 2005-March 2006. The NHA values reported for each month were measured in the last week of each month. Three pasture grazing exclusion cages (1.14 × 0.64 m) were placed in the top, middle and bottom of each plot after mowing the pasture to 2.5 cm height. On the tree plots, the cages were placed in the centre of four nuclei trees between two rows. The residual value was determined by trimming the mowed pasture at ground level with a portable electric sheering hand-piece. The regrowth sample consisted of three metal quadrats (0.1 $m^2$), one from the middle of each cage. The pasture samples were transported to the laboratory for oven drying and weighing. Following each harvest, the grazing exclusion cages were moved to a new location and were not returned to the previous location for at least three months.

In the laboratory, all tree material (small twigs, leaves and bark) and visible dead insects were discarded from the herbage samples by hand sorting. The samples were then hand washed with fresh water to remove any soil contamination and other foreign material that was not hand picked before washing. The clean samples were then dried in a forced draught oven at 80°C for 48 hours. Dried samples were weighed on electronic scale, to two decimal places (d.p). The monthly NHA rate was determined by subtracting the residual values from the final regrowth values. NHA data from individual cuts in each treatment was pooled to provide seasonal and annual totals.

### 3.2.7 Pasture species composition

Pasture species composition was determined only once during the study period. In each plot, a bottom-to-top strip of pasture was trimmed using a portable electric sheering hand-piece. Samples were transported in plastic bags to Massey University laboratory and species composition was determined the same day on the fresh samples. Each sample was thoroughly mixed with hand and sub-samples were used for further processing. Pasture species were hand sorted (plant by plant) into categories (Table 3.1). The sorted samples were oven dried at 80°C for 24 hours and weighed to four decimal points (d.p). The dry weight of each category is presented as a percentage of the combined weight of all species.

### 3.2.8 Statistical analyses

Data were analysed by Analysis of Variance (ANOVA), with general Linear Model (GLM) procedure of the Statistical Analysis System (SAS, 2001), and mean separation was conducted using the Least Significance Difference (LSD) test at the 5 % level. Repeated measures Analysis of Variance was conducted on NHA and tree data to determine the effect of time on pasture production and tree survival and growth, respectively. Since stakes of different diameters were used both for willow and poplar, covariance analysis was conducted to remove the effect of initial diameter differences on tree height. Linear regression analyses were conducted to determine the relationship between NHA and soil moisture, tree height and stem diameter and height and canopy diameter.

# 3.3 Results

## 3.3.1 Rainfall and temperature

Figure 3.2 illustrates the monthly total rainfall along with mean soil and air temperature. Rainfall in October 2004 was sufficient (116.4 mm) to support the establishment of willow and poplar stakes. In December 2004 there was 154.6 mm rainfall and increasing air and soil temperature. The total annual rainfall in 2005 was 886.2 mm with maximum rainfall in October (138.4 mm). The least rainfall was observed in February 2005 (28.4 mm).

The largest mean maximum air and soil temperatures were observed in February 2005 (25.2 °C and 20.4 °C respectively). The smallest minimum air and soil temperature were observed in June 2005 (3.8 °C and 7.8 °C respectively). The soil temperature values at 100 mm depth were between maximum and minimum air temperature throughout the study period (Figure 3.2).

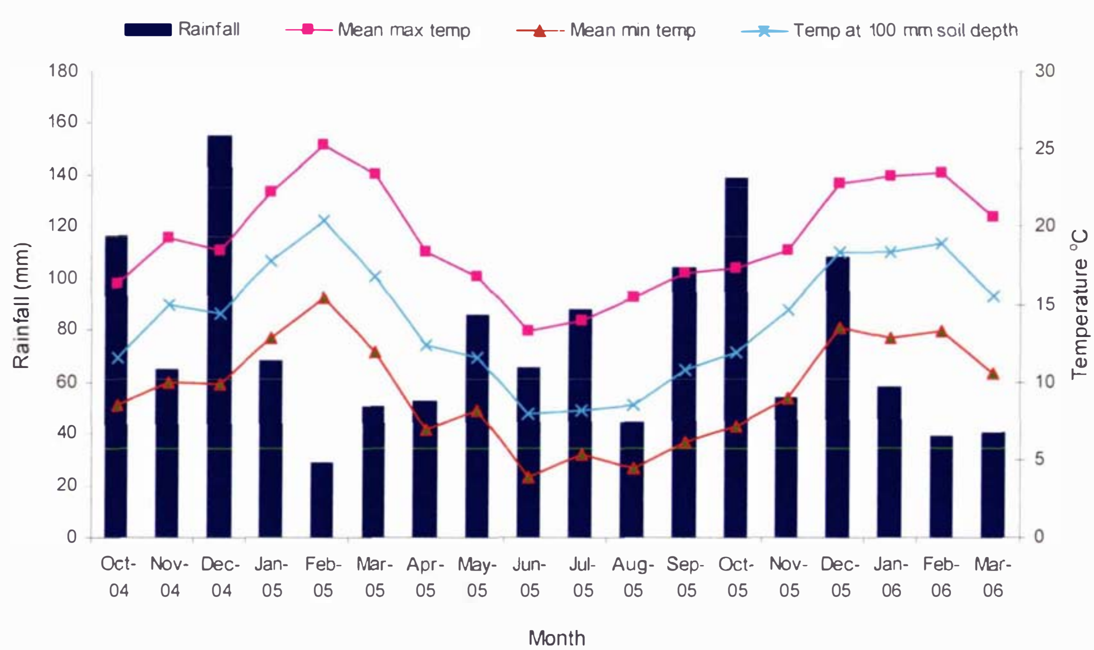


Figure 3.2 Total monthly rainfall (mm) and mean air and soil temperature (°C) during the experimental period in Palmerston North, New Zealand.

(Source: AgResearch)

### 3.3.2 Soil bulk density and Olsen P

Soil bulk density increased with soil depth. The bulk density in the soil surface (0-150 mm) ranged from 1.24 to 1.33 g $cm^{-3}$ and from 1.37-1.45 g $cm^{-3}$ in the 150-300 mm depth. Similarly, the soil bulk density increased with further soil depth and ranged between 1.49 to 1.50 g $cm^{-3}$ in the 300-450 mm depth.

Soil Olsen P values were higher in the top 0-75 mm depth (38 µg $g^{-1}$) than the 75-150 mm depth (20 µg $g^{-1}$). The soil pHs for the 0-75 mm and 75-150 mm depths were 5.7 and 5.6, respectively. However, Olsen P and pHs were similar between treatments ($P > 0.05$).

### 3.3.3 Willow and poplar establishment and growth

The tree survival rates were determined by counting the number of trees alive in each plot at the end of the first and second year. After the first growth year, willow establishment was 100 % followed by poplar with 97.7 %. At the end of the second year, willow maintained 100 % survival but the number of poplar trees decreased to 90.5 %. However, the differences between treatments were not significant ($P > 0.05$) due to marked variations in the individual poplar plots.

Willow trees were significantly taller than poplar ($P < 0.05$) after the first and second year's growth. In the first year, willow gained a mean height of 1.02 ± 0.01 m $tree^{-1}$ while the mean height for poplar was recorded as 0.67 ± 0.01 m $tree^{-1}$. In the second year, willow reached a maximum mean height of 1.90 ± 0.02 m $tree^{-1}$ followed by poplar at 1.35 ± 0.03 m $tree^{-1}$. Similarly, the differences in tree stem diameter were also significant ($P < 0.05$) between treatments. For example, at the end of the first year growth period, willow had a mean stem diameter of 37 .6 ± 0.48 mm $tree^{-1}$ but the mean diameter for poplar trees was 27.9 ± 0.35 mm $tree^{-1}$. The increase in diameter during the second year was also significantly greater ($P < 0.05$) for willow (5.91 mm $tree^{-1}$) than for poplar (4.64 mm $tree^{-1}$) thus gave diameters at the end of the second year of 43.5 ± 0.54 mm $tree^{-1}$ and 32.6 ± 0.37 mm $tree^{-1}$, for willow and poplar respectively. There was not a strong linear relationship between tree stem diameter and tree height (Figure 3.3) but regression analysis between stem diameter and height was highly significant ($P < 0.0001$) ($r = 0.62$). The initial and final stem diameter showed a strong correlation (Figure 3.4) and regression analysis was also highly significant ($P < 0.0001$). There was not a strong linear relationship between tree diameter and number of shoots ($R^2 = 0.4019$), although regression analysis was significant between the stem diameter and the number of shoots ($P < 0.0001$).

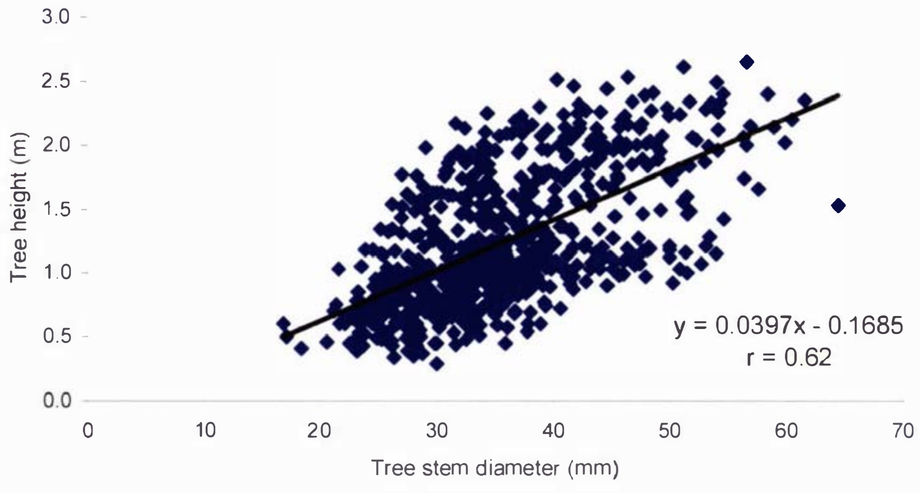


Figure 3.3 Data pattern shows the relationship between the tree stem diameter (mm) and tree height (m) of willow and poplar at Moginie, Manawatu.

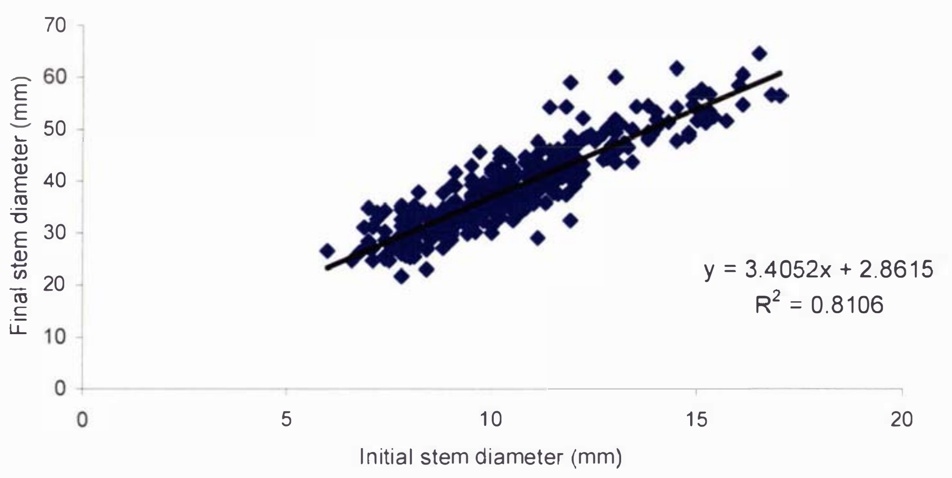


Figure 3.4 Data pattern shows linear relationship between initial tree stem diameter (mm) and final stem diameter (mm) of willow and poplar at Moginie, Manawatu ($n = 342$, $P < 0.0001$).

Willow also produced more first-order shoots than poplar (Plate 3.2a,b). In July 2005, willow had a mean of 9.84 ± 0.21 shoots tree$^{-1}$ while the poplar had only

2.44 ± 0.08 shoots tree$^{-1}$. In the following year, significantly more willow shoots died (1.07 tree$^{-1}$) compared with poplar (0.25 tree$^{-1}$). However, the total number of shoots remained significantly ($P < 0.05$) higher (8.77 ± 0.18 tree$^{-1}$) in willow than poplar (2.25 ± 0.09 tree$^{-1}$).

Canopy diameter for each willow and poplar live tree was estimated with the measurement of radial extension of branches starting from the main stem to the periphery of the canopy of the tree. Willow had a significantly ($P < 0.05$) larger canopy mean diameter (68.9 ± 0.94 cm tree$^{-1}$) than poplar (34.4 ± 1.08 cm tree$^{-1}$). Tree stem diameter was also in good relationship with the final tree canopy diameter (r = 70). The mean canopy area calculated for willow and poplar was 0.38 and 0.10 m$^2$ tree$^{-1}$. This corresponded to 26 % and 7 % of the canopy closure for willow and poplar, respectively.


(a)


(b)

Plate 3.2 (a) Willow shoots at the end of first year growth in willow pasture (WP) treatment at Moginie, Manawatu. (b) Poplar shoots at the end of first year growth in poplar pasture treatment (PP) at Moginie, Manawatu.

Both willow and poplar responded to soil moisture stress by shedding their leaves in summer of 2005 and 2006. However, willow retained their leaves for a longer period than poplar. Poplar shed most of their leaves by the end of May (Plate 3.3a) but willow retained some leaves until the last week of June (plate 3.3b). Willow gall sawfly attack was observed during the early summer of 2004-2005 and of 2005-2006 and lasted until early autumn and damaged some of the leaves. The reddish-brown galls were visible on the leaves (Plate 3.5b). Trees were sprayed twice with Orthene spray chemical. The liquid contains 195 g L$^{-1}$

acephate in the form of a soluble concentrate plus 346 g $L^{-1}$ ethylene glycol. The chemical is absorbed by plant and translocated in the sap stream. This spray was effective in containing serious damage to the tree leaves.

(a) (b)

Plate 3.3 (a) View of poplar defoliation on May 29, 2006 in poplar pasture (PP) treatment at Moginie, Manawatu. (b) View of willow defoliation on May 29, 2006 in willow pasture (WP) treatment at Moginie, Manawatu.

In 2006, sprouting started in late August in willow but poplar leaves did not emerge until late September, when willow trees were almost fully covered with leaves. However, willow leaves did not reach their maximum size until September. Willow produced light green leaves but poplar's newly emerging leaves were of reddish colour (Plate 3.4a,b) exhibiting some aesthetic value in a silvopastoral system.

(a) (b)

Plate 3.4 (a) Poplar leaf sprouting as on 30th September 2006 in poplar pasture (PP) treatment at Moginie, Manawatu. (b) Willow leaf sprouting as on 30th September 2006 in willow pasture (WP) treatment at Moginie, Manawatu.

### 3.3.4 Pasture species composition

The major pasture species present were ryegrass *(Lolium perene L)* and Yorkshire fog *(Holcus lanatus L)* along with white clover *(Trifolium repens)*. Weeds like buttercup *(Ranunculus spp)* constituted 7-11.4 % of the total composition. The partitioning of different botanical components of the sward revealed that *Lolium perene* was the predominant species (Table 3.1) in all the treatments. *Lolium perene* was about 59 % and 60 % in WP and OP while in PP it exceeded 70 %. All other species contributed about 30-40 % of the total composition in all treatments. However, there were no significant differences between the same species between treatments (P > 0.05).

Table 3.1 The spring pasture species composition (%) from willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at Moginie, Manawatu.

| Treatment | Ryegrass | | Fog | | Clover | | Weed | | Other | | Dead | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM | Mean | SEM |
| WP | 59.3 | 11.2 | 20.3 | 9.0 | 3.6 | 1.6 | 11.4 | 1.4 | 2.9 | 1.8 | 2.4 | 0.2 |
| PP | 70.6 | 11.4 | 6.1 | 4.7 | 4.9 | 1.0 | 6.9 | 2.5 | 9.9 | 5.6 | 1.5 | 0.1 |
| OP | 59.8 | 8.7 | 7.3 | 2.3 | 2.2 | 0.5 | 10.1 | 1.9 | 17.4 | 9.5 | 3.1 | 0.7 |

### 3.3.5 Pasture production

The total pasture production for the study period (April, 2005-March, 2006) was significantly different between treatments and was in the order of OP > PP > WP (P < 0.05). The mean annual production in the OP was 13.4 ± 0.23 t DM $ha^{-1}$ $yr^{-1}$ while PP and WP produced 12.2 ± 0.49 and 10.3 ± 0.55 t DM $ha^{-1}yr^{-1}$, respectively.

Overall, month-wise mean daily production (kg DM $ha^{-1}$ $day^{-1}$) was significantly different between WP and the other two treatments but there was no difference between OP and PP (OP = PP > WP, P < 0.05). The mean monthly NHA was 28.2, 33.4, and 36.7 kg DM $ha^{-1}$ $day^{-1}$ in WP, PP and OP, respectively. The individual comparison between treatments on a monthly basis (Fig 3.5) revealed that NHA was significantly higher in OP in the months of December and February than WP ($P < 0.05$) but there were no significant differences between PP and the other two treatments (Figure 3.5). However, in January, NHA was significantly higher in OP than in both PP and WP ($P < 0.05$), but there were no differences between WP and PP ($38 \pm 1.08 > 25.9 \pm 1.44 = 21.6 \pm 3.78$ kg DM ha$^{-1}$day$^{-1}$). The NHA in other months during the study period remained similar in all treatments.

Presumably NHA in March was below zero in WP but remained positive in OP and PP despite some individual sample values being negative (Figure 3.5). Marked variations occurred between plots of all treatments in March. This was most likely due to irrigation in the adjacent experiment (Chapter 5). The irrigation water was blown by wind on to some plots and caused greater pasture growth in some plots at a dry time of the year.

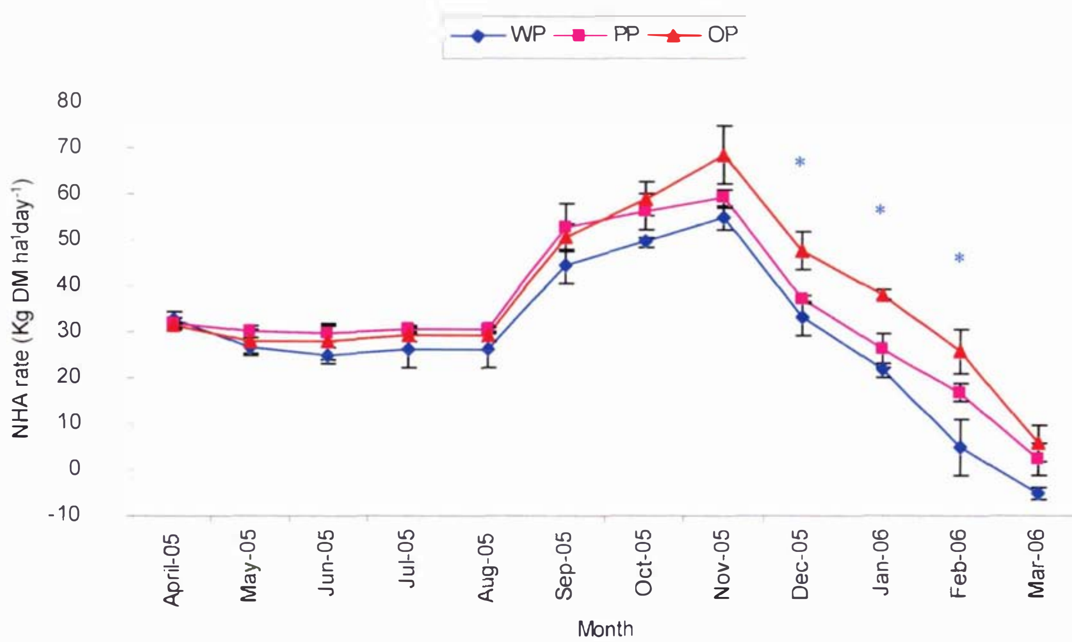


Figure 3.5 Month wise mean daily NHA rate (kg DM ha$^{-1}$ day$^{-1}$) from willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at Moginie, Manawatu. Values for July and August were equally distributed. Bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

Seasonally pooled data revealed that the NHA rate was significantly ($P < 0.05$) lower in WP than OP in spring and summer but PP was not different from other treatments (Table 3.2). The DM production in autumn and winter was similar between all treatments (Table 3.2). The major portion of DM production occurred in spring in WP, PP and OP (47 %, 42 % and 40 %), respectively. NHA rate decreased in summer in all treatments but major reduction occurred in WP (60 %) followed by PP (53 %) and OP (37 %) compared with spring production. Herbage rate further reduced in autumn in all treatments but WP reduced about (50 %) followed by OP (42 %) and PP (19 %) compared with summer, respectively. Nevertheless, autumn was the least contributor to the total herbage production.

Table 3.2 Seasonal NHA rate (kg DM $ha^{-1}day^{-1}$) in willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at Moginie, Manawatu.

| Treatment | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| WP | 49.45 | 19.70 | 10.03 | 25.68 |
| PP | 55.93 | 26.41 | 21.32 | 30.11 |
| OP | 59.20 | 37.08 | 21.68 | 28.77 |
| LSD (0.05) | 7.62 | 11.26 | 14.79 | 3.78 |
| Significance | 0.0427 | 0.0137 | 0.855 | 0.0654 |

## 3.3.6 Soil volumetric moisture content (%)

### 3.3.6.1 0-150 mm depth

At the time of establishment of the experiment, soil moisture contents were close to field capacity (45 %). For example, on 14th October 2004, the soil moisture contents were 46.2 ± 0.25 %, 49.1 ± 2.23 % and 42.6 ± 4.5 % in WP, PP and OP, respectively. However, soil moisture content was not significantly different between treatments ($P > 0.05$) at the start of the experiment. Soil moisture content varied between months and between different dates in the same month in all treatments throughout the study period. The months of winter and spring had higher soil moisture content than summer and autumn months (Figure 3.6).

Significant differences were measured only a few times during the study period. For example, in 2005, the significant differences occurred between treatments only on 6th May when soil moisture content was lower in WP compared with PP (P < 0.04), but OP was not significantly different from PP or WP. However, the differences were not noted again until 30th January, 2006 when WP again had lower soil moisture content compared with PP (P < 0.04), but there were no significant differences between OP and WP or PP. On 7th February, 2006, the soil moisture content in WP was significantly lower than both PP and OP (P < 0.005). However, on 20th February, soil moisture was significantly lower in WP only compared with OP (P < 0.04).

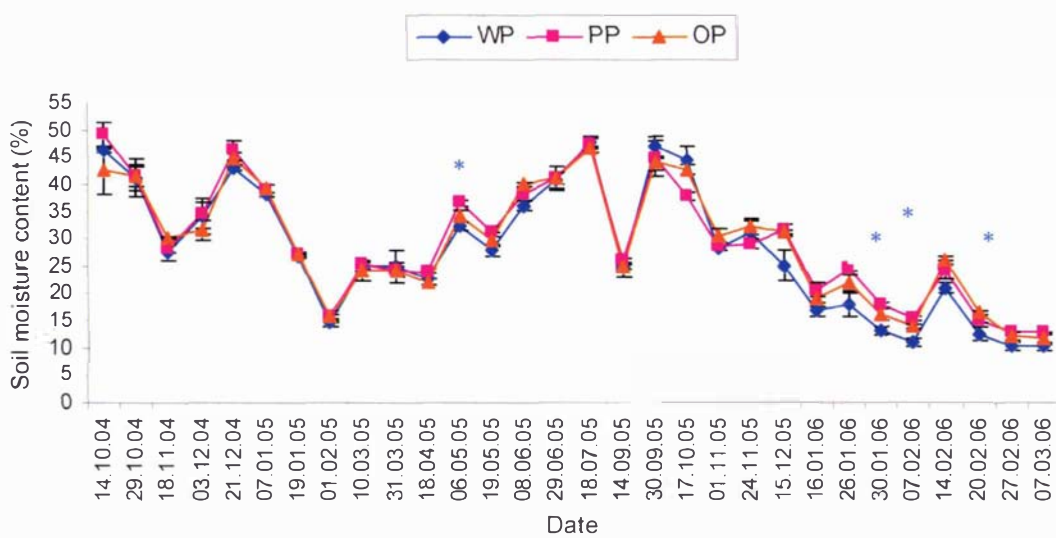


Figure 3.6 Volumetric soil moisture content (%) from willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at 0-150 mm depth at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

### 3.3.6.2 0-300 mm depth

Overall mean soil moisture contents values were not significantly different between treatments (P > 0.05) for 0-300 mm depth. The highest soil moisture contents value in all treatments was found on 18th July 2005 (Figure 3.7), compared with measurements made at all other times during the study period (P < 0.0001). Significant differences between treatments first appeared on 16th January, 2006, when moisture contents were lower in WP compared with OP and PP while values for PP were also significantly lower than OP ($P < 0.01$). Although differences were also found on 26th January, 2006 when soil moisture values were significantly lower in WP compared with both OP and PP ($P < 0.04$) but were not consistent throughout the month and were not significant on 30th January 2006 between the treatments. Significant differences between treatments were again found on 7th February 2006, and were in the order of WP < PP < OP ($P < 0.006$). These differences remained consistent on 7th and 20th February and 7th March, 2006, but not on 14th February, 2006, and were in the order of WP = PP < OP ( $P < 0.05$).

The partitioning of the soil moisture contents between 0-150 mm and 150-300 mm depths further confirmed that trees were using more water in summer at 150-300 mm depth than pasture alone with significant differences at only three occasions (Appendix 3.1). The differences were noted on 16th January, 2006, when OP had significantly higher moisture content compared with WP ($P < 0.04$), but PP was not significantly different from WP and OP. On 7th February 2006, the soil moisture contents were significantly higher in OP compared with WP and PP ($P < 0.021$), but no significant differences were found between WP and PP. A similar trend was found on 20th February 2006, but not on 14th February, or on 7th March 2006 when measurements ceased.

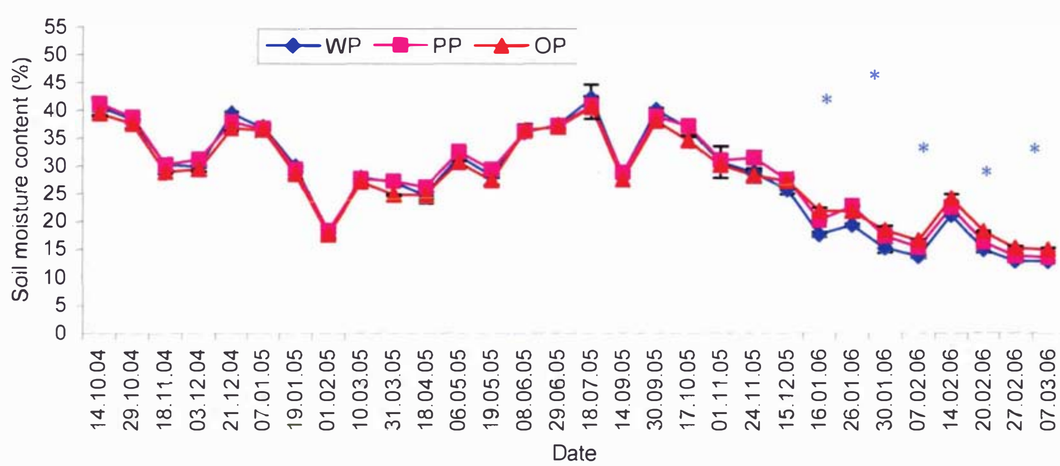


Figure 3.7 Volumetric soil moisture content (%) from willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at 0-300 mm depth at Moginie, Manawatu. The line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

#### 3.3.6.3 0-450 mm depth

The soil moisture contents for the 0-450 mm soil depth varied with time within the same treatment and were significantly higher on 14th October, 2004 compared with all other times, except from soil moisture content on 18th July, 2005 and 30th September, 2005 ($P < 0.0001$). However, there were no significant differences (Figure 3.8) between treatments throughout the study period ($P > 0.05$).

The calculation of soil moisture content for 300-450 mm depth (Appendix 3.2) revealed that the soil moisture contents difference between treatments remained non-significant throughout the study period except for some unknown reasons on 17th October 2005, when values for PP were significantly higher compared with OP and WP ($P < 0.05$). Therefore, results indicated that trees were not affecting soil moisture below 300 mm depth at this age. Though not significant, there was a general trend in soil moisture being lower in PP in late summer 2006 than WP and OP, suggesting that poplar roots were probably extending deeper than willow.

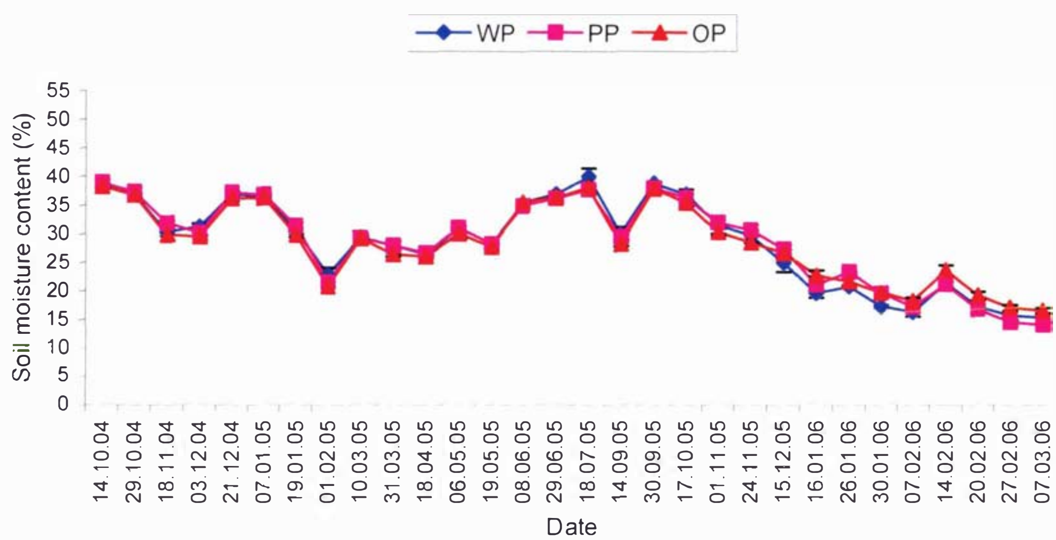


Figure 3.8 Volumetric soil moisture content (%) from willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at 0-450 mm depth at Moginie, Manawatu. The line bars show the SEM for each treatment.

### 3.3.6.4 Moisture content and pasture production

Overall, there was no linear relationship between soil moisture at 0-150 mm depth and pasture production for all the months but a logarithmic relationship existed. However, a good linear relationship existed from September to April in all treatments (Figure 3.9). The relationship was in the order of PP ($R^2$ = 0.9392) followed by WP ($R^2$ = 0.8668) and OP ($R^2$ = 0.8633).

Regression analysis between mean monthly pasture DM production and soil moisture from September to April was highly significant (P = 0.001) in all treatments. The regression equation for each treatment is given below.

WP (kg DM $ha^{-1}$ $month^{-1}$) = -362 + 49.3 $^{moisture}$

$R^2$ = 0.87

PP (kg DM $ha^{-1}$ $month^{-1}$) = - 640 + 64.4 $^{moisture}$

$R^2$ = 0.94

OP (kg DM $ha^{-1}$ $month^{-1}$) = -168 + 52.5 $^{moisture}$

$R^2$ = 0.86

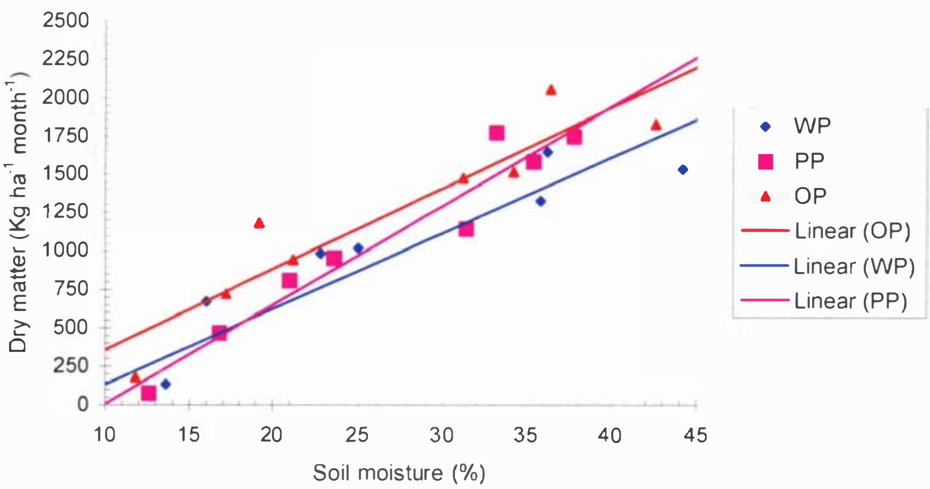


Figure 3.9 Relationship between soil moisture at 0-150 mm depth and NHA rate (kg DM $ha^{-1}$ $month^{-1}$) from September-April. Moisture data is the mean for each month from willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at Moginie, Manawatu.

NHA also reduced sharply in all treatments from November, 2005 to March, 2006 as a consequence of the decrease in soil moisture level. Significant differences in NHA between treatments were also restricted to summer months and coincided with soil moisture stress periods. Like soil moisture, NHA was also significantly less in WP and PP compared with OP. This coincidence of smaller soil moisture content with decreased NHA indicates that trees were using more soil water during summer months than pasture alone.

# 3.4 Discussion

## 3.4.1 Willow and poplar establishment and pasture growth

In New Zealand, willow and poplar unrooted cuttings (stakes) are usually planted in August and September (Evans, 1973) but due to unavoidable circumstances, the planting for this particular experiment was in October (2004). Despite the later timing of planting, willow and poplar had 100 % initial sprouting and started growing well (Plate 3.1b). This was partly due to a good level of soil moisture (> 40%) in the upper soil depths (0-150 mm and 0-300 mm depth) during the month of planting. However, as expected, during summer the soil moisture level decreased to wilting point (15.3 %) in late January 2005. At this stage, there was premature leaf fall, likely due to soil moisture stress (McElwee & Knowles, 2000). At this stage the plots were irrigated weekly using water from a nearby small dam through a sprinkler system until sufficient rainfall occurred (Plate 3.5a).This provided relief from moisture stress to the plants and the opportunity for growth during summer. Positive effects of irrigation on poplar tree survival have been reported in South Carolina, USA (Coylea et al., 2006). Despite a few losses among poplar plants, the overall plant survival was satisfactory by the end of the first year for both willow and poplar (100 % vs 97 %), respectively. However, during the 2$^{nd}$ year, more poplar plants died and the survival rate dropped down to 90 %, but willows maintained a 100 % survival rate.

The survival rates for both willow and poplar indicated that establishment through unrooted stem cuttings (stakes) can give satisfactory results. Hathaway (1986) also noted that use of unrooted stem cuttings was one of the most convenient methods for establishing *Populus* and *Salix* species. Coylea et al., (2006) evaluated 31 different poplar clones (comprised of both pure species and hybrids) and reported that survival rate differed significantly among clones and varied between 27 % to 96 % and 25 % to 72 % in the first and second year of the study, respectively. However, four of the five clones with the highest survival were hybrids. Douglas et al., (2003) reported an overall 93 % and 90 % survival rate for Tangoio willow after the 1$^{st}$ and 2$^{nd}$ year's growth, respectively.

However, different stake sizes were used and results varied with the size of stakes. The trial was located on a sheep and beef farm near Takapau in central Hawke's Bay, with different climatic conditions and unlike the current study, the plants were never irrigated during drought. The use of unrooted cuttings has been evaluated for *Pinus radiata* on a trial basis in New Zealand at different sites in Bay of Plenty/ South Waikato region with survival rates varying from 21 % on a farm site, to 75 % on a V-bladed cutover site (cultivated ground) (Anon, 1995). This propagation method has the advantage of improved tree form and stability against wind damage and reduced cost per plant (Anon, 1995; Zsuffa, 1992). Unrooted stem cuttings of willow produce as much foliage as rooted stem cuttings but provide cheaper establishment than rooted cuttings (Oppong, 1998). Sulaiman (2006) reported that survival rates ranged between 91 % to 99 % and 92 % to 100 % for Tangoio willow and Veronese poplar for different sized unrooted stem cuttings and planting depths, respectively.

The tree survival rate for willow and poplar has been linked to stem cutting diameter, with higher survival for thick stem cutting (Sulaiman, 2006), probably due to higher nutrient and carbohydrate reserve. However, Poplar losses in the current study were not specifically linked to any stem diameter class.

(a) (b)

Plate 3.5 (a) Irrigation in willow pasture (WP) and poplar pasture (PP) treatments using sprinkler system during drought in summer 2005 at Moginie, Manawatu. (b) Willow gall saw fly (*Pontania proxima)* attack (reddish brown galls) on leaves during summer at Moginie, Manawatu.

Willow grew faster than poplar and produced more shoots, thereby giving a significantly larger canopy diameter ($P < 0.05$). Douglas et al., (2003) reported the longest regrowth shoot ranging from 0.3-1.1 m for Tangoio willow across different treatments involving different size stakes and cutting heights. Oppong (1998) reported that leader length ranged from 1.0 to 1.8 m while the number of shoots ranged from 38 to 48 for Tangoio willow after initial coppice cuts made in different seasons (winter, spring and summer). These shoot numbers are greater than the numbers compared with the number reported in the present study and are due to frequent coppicing and the fact that the willow trees were established two years prior to the start of the experiment. Sulaiman (2006) reported higher shoot number (up to 16) for Tangoio willow compared with Veronese poplar (up to 7).

The shoot number and canopy diameter increased with increase in stem diameter, probably because higher food reserves in the beginning help produce more shoots in thicker stem cuttings leading to larger canopy diameter later on. For example, Kozlowski (1971) reported that current-year shoots of deciduous trees depend for their early growth on stored resources in older stems. Similarly, large stem cutting at planting has been reported to encourage early fruit production in apple (Van Oosten, 1978). Sulaiman (2006) also reported that stem diameter had significant positive effect on tree shoot number, length and canopy diameter in Tangoio willow and Veronese poplar. Also, the basal stem cross-sectional area of the first order branches of *Betula maximowicziana, Acer mono var. mayrii and Quercus crispula* (deciduous trees) has been found to be proportional to the number of current year shoots on such branches (Suzuki, 2003).

The difference in timing of sprouting at the start of growing season (Plate 3.4a, b) between willow and poplar reflects the genetic trait of the species and may have consequences for the early fodder and final biomass production. For example, Ronnberg-Wastljung (2001) has shown that, in willows, the phenology of bud burst is under strong genetic control. Also, plants that start growing rapidly early in a season (rapid starters) might gain a great advantage in annual production compared to those starting growth slowly or later in the season (slow starters) (Kopp et al., 2001). Weih & Nordh (2002) reported that most willow clones with very low initial plant biomass grew to relatively small final biomass and additional biomass gain late in the season hardly compensated for the slow growth of slow starters early in the season.

The willow and poplar responded to water stress during late summer and early autumn by shedding leaves. Leaf shedding is a common phenomenon during drought. For example, Roygard (1999) reported that *S. kinuyanagi* and *E. nitens* responded to water stress by shedding leaves. Leaf loss occurs to different degrees in most species, covering the range from evergreen to fully deciduous trees (Williams et al., 1997). However, Johnson et al., (2002) reported a similar response by willow and poplar to water stress. Besides loss of leaves, drought can also result in desiccation of roots and twigs (Vesk & Westoby, 2003). Tyree, et al., (1993) reported that due to drought, leaves turned yellow and the petiole lost hydraulic conductivity by 87 % leading to leaf shedding. Other possible reasons for leaf shedding could be greater leaf desiccation and light intensity (Laurance et al., 2003).

Under canopy closure of 26 %, the annual net herbage accumulation (ANHA) in WP treatment was 77 % of that of OP. Similarly, under 7 % canopy closure, PP produced 91 % ANHA of that of OP. This indicates that willow can affect understorey pasture growth more than poplar, most likely because of their fast growth, bigger crown and greater number of shoots. On the other hand, all these growth components indicate that willow are capable of producing more fodder and biomass. However, the negative effects of trees on understorey pasture growth can be minimised through silvicultural management practices such as thinning, pruning, browsing and coppicing etc.

The results presented here are in agreement with the previous research conducted under broadleaved trees in New Zealand. For example, Wall (2006) concluded that in summer the canopy closure was strongly related (inversely) to stand level photosynthetically active radiation (PAR) transmission ($r^2$ = 0.88-0.97; $P < 0.0001$) and was one of the best stand density indices to estimate PAR transmission, especially for the central point (Zone 3) between four nuclei trees. The same author reported that annual NHA under poplar canopy closures of 25, 50 and 75 % was 77, 60 and 48 % of the open pasture, respectively. It was further noted that in the vertically projected gap between the four nuclei trees, the annual NHA decreased by 6.6 % relative to open pasture for each 10 % increase in canopy closure. Similar results were reported by Buckley, et al., (1999), who found similar relationships for stands dominated with either deciduous oak *(Quercus rubra L.)* or evergreen red pine *(Pinus resinosa Ait)*. Nevertheless, there were notable differences in the methodologies used in both studies. In the study of Buckley et al., (1999), light measurements were based on instantaneous quantum-sensor readings and canopy closure was determined with a concave spherical densitometer while Wall (2006) compared digital photos with measurements of diffuse non-intercepted radiation (DIFN) from spherical light meters. Dodd et al., (2005) conducted a field study on the effect of shade on pasture growth by creating different levels and durations of shade artificially. The authors reported that ANHA decreased significantly under increasing levels of shade. It was further noted that the level of shade accounted for 68 % of the variation while shade duration accounted for only 6 % of the variation in NHA. Power et al., (1999) showed linear decreases in pasture relative yield with increasing shade for *E. nitens* and *P. radiata*.

Similarly, Guevara-Escobar (1999) reported 60 % less pasture production under mature poplar trees compared with open pasture. Douglas et al., (2001) studied the effect of 8-15 years old poplar on understorey pasture growth from two different sites and reported up to 14% less production under trees compared with open pasture. Authors from both studies determined that shade was the major factor in reduced pasture growth. Conversely, Gilchrist et al., (1993) did not find significant differences in pasture production under individual trees, including willow and poplar at distances between 1-13 m from the tree trunk ($P > 0.05$). No measurements for light or soil moisture content were reported. Though not significant, it was argued that eucalypts, being an evergreen species, appeared to depress pasture growth more compared with willow and poplar.

In general, plant morphology is affected by changes in the intensity of PAR (Devkota, 2000; Lieffers et al., 1999). The reduced levels of PAR in the range of tree-shade causes a decrease in tiller/branch appearance (Devkota et al., 1997; Gautier et al., 1999) and root biomass (Wilson, 1997). According to the model developed by Wall (2006), tiller/branch production per plant in the perennial ryegrass/white clover sward would cease at around 85 % canopy closure in summer.

Tree spacing (stocking rate), age, and the nature of trees (evergreen vs deciduous) also determine the level of pasture growth in a silvopastoral system. Hawke (1991) reported a clear pattern of decreasing pasture yields, with increasing tree stocking and age. For example, it was reported that there was an increase in pasture production under trees at the spacing of 50 stems ha$^{-1}$ of *Pinus radiata* relative to open pasture in year three but a 15 % decline after 13 years. At the higher stocking rate of 200 stems per ha, the pasture yield fell 82 % after 13 years. Similarly, it has been reported that increasing tree age and stocking can reduce the livestock carrying capacity (Percival & Hawke, 1985). However, the effect of increasing tree stocking rate and age can be offset by good farm management and silvicultural practices.

The reduction in pasture growth in summer may not be a function of canopy closure alone. For example, in temperate climates, the intensity of PAR in summer may exceed the photosynthetic capacity of pasture plants. Therefore, even under moderate levels of shade the intensity of PAR may still actually exceed, or at least be near, the understorey plant's maximum photosynthetic capacity, thereby having little effect on growth and development (Wall, 2006). Conversely, in winter, the intensity of PAR in the open is normally much lower than in summer and a similar level of shade in this season would likely have a greater impact on growth of the understorey plants (Wilson, 1997).

The response of pastures to changes in the level of light is also influenced by the water availability and temperature (Alberda, 1965; Sanderson et al., 1997). Under limited temperature or water, the photosynthetic response of a plant reaches its maximum at a lower level of light compared to when these abiotic factors are non-limiting for plant growth and development (Alberda, 1965; Wilson, 1997). Thus, a moderate decrease in the level of PAR from open pasture values may have little impact on plant growth and development when other abiotic factors are limiting. However, when under certain situations the tree canopy improves the above abiotic factors, the understorey photosynthesis can increase in full sunlight relative to open conditions (Wild et al., 1993; Wilson, 1996; Wong & Wilson, 1980).

### 3.4.2 Soil moisture content and relationship with NHA

Differences in soil moisture content at all depths remained non-significant between treatments throughout the first year of growth after planting the willow and poplar. Significant differences were not expected during this period because of the very small size of willow and poplar trees. Also, root systems were likely to be developed very little. Heilman et al., (1994) showed that after the first year of growth, first order roots originating from the sides of cuttings in different poplar clones were, on average, only 54 cm long. However marked variations were observed between different clones with root lengths as small as 12 cm for some clones. Soil moisture content decreased sharply from October 2005 onward and reached stress level (< 25 %) in December. In peak summer and early autumn (January-March) the values for soil moisture content decreased further and were below wilting point (<15.3 %) (Gradwell, 1974) at times in 0-150 and 0-300 mm depths, as a consequence of increased temperature, less rainfall and increased evapotranspiration in all treatments.

Statistically significant differences in soil moisture content at 0-150 mm and 0-300 mm depth between treatments were apparent in the second year but were restricted to summer and some autumn months (March). However, the decrease in soil moisture in WP was more severe, than OP while PP fluctuated between WP and OP. The differences in soil moisture content in the soil stratum below 300 mm depth remained non-significant throughout the study period except for a single incidence on 17$^{th}$ October 2005, when moisture contents were higher in OP compared with WP and PP (Appendix 3.2). The apparent differences in soil moisture to a depth of 300 mm coincided with the planting depth of the willow and poplar. This indicates that most of the willow and poplar roots were within the 0- 300 mm depth.

Studies in the temperate zone, humid tropics and semi arid tropics have shown that the greatest tree roots density is in the top 300 mm of soil (Imo & Timmer, 2000; Jose et al., 2000; Lehmann et al., 1998). Puri et al., (1994) studied the distribution of coarse and fine roots of nine year old *Populus deltoides* and reported that most of the coarse roots were distributed in the top 300 mm of soil, whereas fine roots were concentrated in the top 150 mm. Similarly, Jose et al., (2000) reported that the root systems of 11 year old black walnut and red oak were found to mostly occupy the top 300 mm of soil and decreased in density with depth.

Mclvor et al., (2006) studied three different aged (5, 7 and 9 yrs) Veronese poplar *(Populus deltoides × nigra)* root architecture and distribution systems in New Zealand hill country and reported that radial structural roots (≥ 2 mm diameter) were generally within 400 mm of the ground surface, with many being located within 150 mm of the surface. It was also observed that roots growing downslope rarely grew below 100 mm of the soil surface, except at their terminus. Douglas et al., (2006) reported that the soil water content in open-pasture was 8 % higher (0.26 $m^3$ $m^{-3}$) in summer than beneath (2 m from tree stem) 8-11 years old poplar trees (0.24 $m^3$ $m^{-3}$) at 0-200 mm depth.

Soil water stress causes reduction in tiller density and rates of leaf extension and appearance in grasses (Barker et al., 1985). Water stress also causes large reductions in plant height (Robertson, 1994) and leaf area (NeSmith & Ritchie, 1992). The competitive interactions between trees and understory crop for soil water become more intense as soil water is depleted (Miller & Pallardy, 2001). Jose et al., (2004), in their review "Interspecific interactions in temperate agroforestry" based on data from site-specific research and demonstration trials from temperate agroforestry systems, primarily from temperate North America, showed that competitive interactions involving water seem to be the most influential driving force of productivity in both alley cropping and silvopastoral systems.

In the current study, although soil moisture deficiency affected NHA rate during summer, the quantification of the loss of pasture growth due to moisture stress is not possible in the presence of shade. In other words, in the absence of light intensity data from the experimental site, the degree of influence between soil moisture and shade can only be speculated. However, pooled seasonal data revealed that spring production was significantly less under willow pasture compared with open-pasture. This shows that the shade effect started in spring, a period when soil moisture was not limiting pasture growth. In this period shade influenced pasture growth more than soil moisture.

## 3.5 Conclusions

Willow and poplar establishment using unrooted stem cuttings was a successful and convenient method that produced good results despite delayed planting. The willow and poplar survival rate was similar (100 % vs 95 %) after two years, respectively. Willow grew faster than poplar and gained greater height (1.90 vs 1.35 m), stem diameter (43.5 vs 32.6 mm) canopy diameter (68.90 vs 34.41 cm) and number of shoots (8.77 vs 2.25) at the age of two years, respectively. Initial stem diameter was in a strong linear relationship with final stem diameter ($R^2$ = 0.81).

The willow and poplar significantly reduced understorey pasture growth in their second year mainly due to shade and some soil moisture effect in late summer. The total annual pasture production in willow pasture and poplar pasture was reduced by 23 % and 9 % compared with open-pasture (10.3, 12.2 vs 13.4 t DM $ha^{-1}$ $yr^{-1}$), respectively. The mean monthly NHA was 28.2, 33.4, and 36.7 kg DM $ha^{-1}day^{-1}$ with major pasture production in spring in WP, PP and OP (47 %, 42 % and 40 %), respectively. The effect of trees on soil moisture content was within 300 mm soil depth in summer. The canopy diameter gave a good measure of PAR transmission and shade between four nuclei trees. Willow and poplar had 26 % and 7 % canopy cover in the 2$^{nd}$ year.

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# PASTURE GROWTH IN A WILLOW BROWSE BLOCK

## Table of contents

# 4.1 Introduction

In addition to their primary role as soil conservation trees, willow and poplar are also used in a variety of other situations, including provision of livestock fodder, during times of drought (Cameron, 2003). In summer dry hill country, such as in the Wairarapa, lack of soil moisture in summer and autumn restricts pasture growth (Radcliffe, 1975). Farmers obtain tree fodder by pruning and pollarding soil conservation trees, by coppicing or grazing livestock on fodder blocks, or by taking advantage of leaf fall from trees. Under a Sustainable Farming Fund Project, the Ministry of Agriculture and Forestry (MAF) has taken steps to enhance the concept of tree fodder use on livestock farms in New Zealand (Charlton et al., 2003).

Several willow species are used as fodder trees with varying regrowth rates after harvest. For example, S. *matsudana* has been found to perform reliably whereas Pussy willow's (*S. x calodendron* and *S. x reichardtii)* soft and palatable bark has been reported an easy target for ring barking (Olsen & Charlton, 2003). Douglas et al., (1996), and McCabe & Barry (1988) have also evaluated several species/clones of willow in trial fodder blocks, with the most promising being the tree willow hybrid *Salix matsudana* × *alba* clone 'Tangoio'. Tangoio is palatable and productive, has good nutritive value (McCabe & Barry, 1988) and is one of the most drought tolerant of the willows (Douglas et al., 1996; Moore et al., 2003). However, *S. kinuyanagi*, *S. viminalis* 'Gigantea' and *matsudana* × *alba* 'Wairakei' have also shown potential in fodder block plantations (Douglas et al., 2003).

Several farmers also use trees in coppices in the southern North Island. The terms "coppice block" and "browse block" are synonymous, with only minor differences in silvicultural and grazing management practices. Such blocks usually comprise of willow (Charlton et al., 2003) planted close together, usually in rows (Kemp et al., 2001) enabling a block to be grazed row-by-row using an electric fence to ration the fodder.

The main purpose of planting fodder trees, especially willow browse blocks, on farms is to produce a potential source of supplementary forage (green) during summer. Secondly, due to the ability of willow to grow in swampy pastures, the underused areas on farms could possibly be made more productive (Douglas et al., 2003). Forage from trees can benefit farm animals by providing green fodder in droughts and benefit the farmers by reducing labour cost by grazing ewes on these fodder blocks during mating (Pitta et al., 2005).

Willow can offer better forage than drought pasture (Kemp et al., 2003) with reasonable nutritive value and digestibility (Douglas et al., 1996; Oppong et al., 2001) in summer and autumn, a time when it is most needed due to low rainfall resulting in low pasture production (Oppong et al., 1996). Willow browse block studies have shown promising results with regard to the maintenance of ewe health and reproductive performance (Pitta et al., 2005; Pitta et al., 2006). Supplementing with willow tree trimmings can increase conception rate and fecundity in sheep while lamb mortality could be reduced compared with grazing drought pasture (McWilliam, 2004).

Silvopastoral systems aim at sustainability and efficient use of natural resources on farms and willow browse blocks are required to be understorey pasture friendly. Numerous studies in the past (Douglas et al., 2001; Guevara-Escobar, 1999; Wall et al., 1997) and chapter three of this thesis have shown adverse effects of trees on understorey pasture growth in New Zealand. It is also known that willow tree biomass in a browse block planted at high density (>6000 stems $ha^{-1}$) remains less than 20 % of that of the understorey pasture (Douglas et al., 2003). It is evident that though willow browse blocks can help supplement forage during droughts, the understorey pasture will remain the major feed source for livestock in such a system. Therefore, it is important to have good pasture growth in these willow browse blocks. This is only possible through best management practices that take into account all the environmental factors that are affected by trees that might limit pasture growth in such blocks. The implementation of such practices will require assessment and quantification of these factors. Currently, knowledge about such factors in browse blocks is lacking in New Zealand, prompting the need for such a study. Therefore the objectives of this trial were to:

(i) investigate the changes in soil moisture content in a willow browse block in comparison with rotationally grazed open pasture,

(ii) determine the pasture growth differences between open pasture and in a willow browse block in relation to tree shade and soil moisture effect,

(iii) measure the effect of late spring browsing on willow leaf area development and its implications for understorey pasture growth, and

(iv) study other possible factors such as pasture species composition, that may influence pasture growth.

## 4.2 Materials and methods

### 4.2.1 Site description

The experiment was conducted at Massey University's Riverside Farm, located 15 km north of Masterton. The soil type belongs to 'Otukura Soil Series' (Terrace Colluvium Component) (Pollok et al., 1994). The top soil (average 18 cm) is silt loam while the subsoil is silty clay loam. The site is characterised by low productive rush infested swamp and low lying wet areas. Due to water logging, water-table is reduced by open drains. Willow were established in 2001 from stakes (0.7 m long) at 1.2 m × 1.2 m spacing procured from Wellington Regional Council's Akura Nursery, near Masterton (Dipti Pitta, Personal communication). The cultivar planted in this particular block is *Salix viminalis* 'Kinuyanagi' (PN 386). Willow block was established at the toe of a steep hilly terrain and site hydrology was quite complex due to water seepage (section 6.5). Willow were browsed with sheep in late November 2004 and fenced before WP plots were closed to further grazing. However, OP plots were grazed rotationally with sheep through out the period of trial.

### 4.2.2 Experimental design and treatments

Four willow plots (10 m × 5 m) were randomly selected in close proximity within a 1.5 ha willow block. The plots consisted of willow trees that have been grazed previously with sheep twice every year after being coppiced to stump level in their second winter. Four pasture plots of the same size were also selected in a nearby area. Thus, the experiment consisted of two treatments; willow pasture (WP) and open pasture (OP), with four replicates of each treatment.

### 4.2.3 Soil sampling and laboratory analyses

#### 4.2.3.1 Olsen P

Soil samples were collected from all WP and OP plots using a soil auger. Each sample consisted of five sub samples taken diagonally across each plot at 0-75 mm and 75-150 mm depths. Samples were analysed for Olsen P and soil pH using the methodology described in section 3.2.4.1.

#### 4.2.3.2 Soil bulk density

Soil samples were collected from two randomly selected positions from two plots in each treatment using Aslam's root/soil corer (Aslam, 2005). The corer was vertically driven into the soil to 450 mm depth. After taking the corer out of the ground, a single soil sample (450 mm long) was released on a graduated wooden board and then divided into three equal parts of 150 mm length. This corresponded to soil depths of 0-150 mm, 150-300 mm and 300-450 mm. The process was repeated twice in each plot. Soil dry bulk density was measured using the method explained in section 3.2.4.2.

### 4.2.4 Soil moisture content measurement

Soil volumetric water content ($m^3$ $H_2O$ $m^{-3}$ soil) was measured using the technique explained in section 3.2.5. A single set of probes (150, 300, and 450 mm long) was vertically inserted permanently in the centre of each plot (250 mm from tree) and measurements were made monthly. However, soil moisture was measured twice in February and March 2005. No measurements were made in July and August 2005 due to soil saturation and no differences were expected between treatments during winter. The November 2005 data are missing due to suspension of study for one month.

### 4.2.5 Pasture dry matter sampling

Pasture samples were obtained for monthly NHA from November 2004 to October 2005 using the technique described in section 3.2.6. Two grazing exclusion pasture cages (1.14 × 0.64 m) were placed randomly in the upper and lower half of each plot. The sample size consisted of two 0.1 $m^2$ quadrats from each location. Cumulative pasture growth (ungrazed and unmown) was also measured from the end of November 2004 to July 2005. Sample size and location were the same as for the NHA measurements. Cumulative herbage was only monitored in the willow pasture treatment.

### 4.2.6 Pasture species composition

Pasture species composition was determined twice during the study period. Composition was determined in late March between cumulative herbage (ungrazed and unmown) in WP and OP (grazed and mown) and again in spring to compare mown and grazed composition between WP and OP. The composition was determined using similar methodology as described in section 3.2.7.

### 4.2.7 Leaf area measurement

Eight willow trees were selected (two from each plot) to measure the change in leaf area from December 2004 to April 2005 and from December 2005 to April 2006. The selected trees were of different sizes to represent the overall size difference in the willow browse block. A cage was placed around each monitor tree to protect it from accidental grazing. Leaf area measurements were made monthly by leaf counts and leaf sample collection. Samples of different sized leaves were collected randomly from each tree at the time of leaf count. Samples were transported in a chilly bin to avoid drying of leaves on the way to Massey University, Palmerston North.

The leaf area of sampled leaves was measured using a Li-3100 area meter (Licor-ine, Lincoln, NE) at Plant Growth Unit, Massey University. The total leaf area of each tree was determined by multiplying the mean leaf area of sampled leaves by the total number of leaves for that particular tree.

### 4.2.8 Light and tree canopy measurement

Photosynthetically active radiation (PAR) under trees in WP was measured in February and March 2006, using a light meter (LI – 250, LI – COR, Inc. Lincoln, Nebraska USA). PAR was measured under four nuclei trees from four sides (NSEW) of each tree at close to tree stem, between stem and canopy edge and close to the canopy edge. Tree height and canopy circumference (at the maximum spread) were also measured once in February for the same four nuclei trees in each plot.

### 4.2.9 Statistical analyses

Data were analysed by Analysis of Variance (ANOVA), with general Linear Model (GLM) procedure of the Statistical Analysis System (SAS, 2001), and mean separation was conducted using the Least Significance Difference (LSD) test at the 5 % level. Repeated Measures Analysis of Variance was conducted on NHA and soil moisture content to determine the effect of treatments on pasture production and soil moisture content over time. Simple linear regression analyses were conducted to determine the relationship between NHA with soil moisture content and leaf area.

## 4.3 Results

### 4.3.1 Olsen P

Soil Olsen P was not significantly different (P > 0.05) between treatments at either the 0-75 mm or 75-150 mm depth intervals (Table 4.1). Within the same treatment, the values decreased significantly (P < 0.05) in the 75-150 mm depth compared with 0-75 mm. Soil pH was also similar between treatments (P > 0.05) and there was no variation in pH level between soil depths.

Table 4.1 Soil Olsen P (μg $g^{-1}$) and pH in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | P at different depths (mm) | | pH at different depths (mm) | |
|---|---|---|---|---|
| | 0-75 | 75-150 | 0-75 | 75-150 |
| WP | 20.7 | 11.2 | 5.3 | 5.4 |
| OP | 24.6 | 10.2 | 5.5 | 5.5 |
| SEM | | | | |
| WP | 2.08 | 1.27 | 0.03 | 0.01 |
| OP | 0.92 | 0.53 | 0.02 | 0.04 |
| Sig. | 0.0936 | 0.5001 | 0.0796 | 0.0796 |

### 4.3.2 Soil Bulk density

Soil dry bulk density was similar between treatments (P > 0.05) in the top 0-150 mm soil depth (Table 4.2). However, bulk density increased in deeper soil depths (150-300 mm and 300-450 mm) and was significantly different (P < 0.05) between WP and OP. Marked increases in soil bulk density occurred from the 0-150 mm to 150-300 mm depths. For example, bulk density increased by 32 % and 25.5 % in the 150-300 mm soil depth compared with the 0-150 mm depth in WP and OP, respectively. The bulk density further increased in the 300-450 mm depth in WP and OP (37 % vs 35 %, respectively), compared with 0-150 mm depth. However, the increase between the 150-300 mm and 300-450 mm depths was 7 % and 13 % in WP and OP, respectively (Table 4.2).

Table 4.2 Soil bulk density (g $cm^{-3}$) in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | Depth interval (mm) | | |
|---|---|---|---|
| | 0-150 | 150-300 | 300-450 |
| WP | 0.70 | 1.03 | 1.11 |
| OP | 0.64 | 0.87 | 0.99 |
| SEM | | | |
| WP | 0.02 | 0.02 | 0.006 |
| OP | 0.02 | 0.007 | 0.01 |
| Sig. | 0.0651 | 0.0007 | 0.0004 |

## 4.3.3 Rainfall

The month wise total rainfall is given in Figure 4.1. The total rainfall in 2005 was 757 mm with highest rainfall in March, 2005 (187 mm) and lowest in February 2005 (13 mm). Overall the summer of 2004-05 was wetter with 176 mm rainfall than the summer of 2005-06 with 137 mm. However, winter and spring, 2005 had similar rainfall.

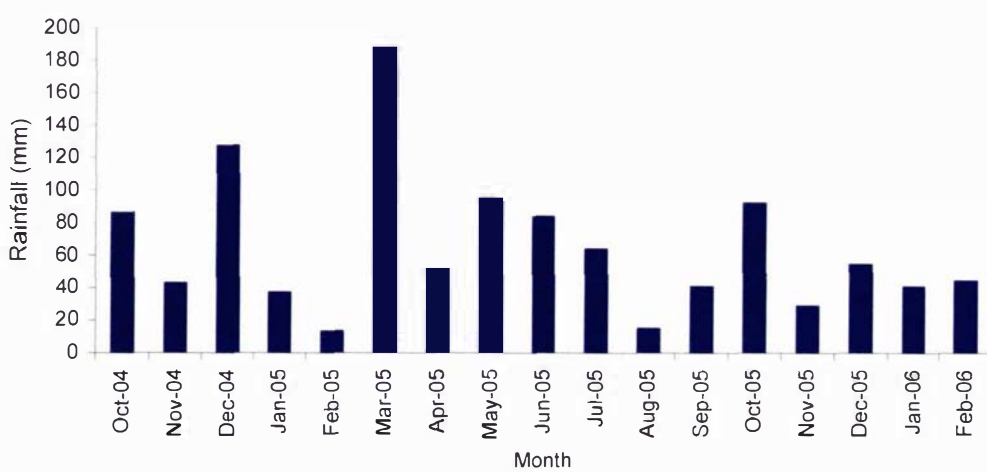


Figure 4.1 Monthly rainfall (mm) for Massey's Riverside Farm, near Masterton, Wairarapa. Data were obtained from Wairarapa College Air Quality Site (Coord NZMG 1949 E2732767 N6024886).

Source: Mike Gordon, Hydrologist System Support Officer. (Personal communication). Mike.gordon.@gw.govt.nz

### 4.3.4 Pasture species composition

In early autumn, the major species present in the sward were ryegrass (*Lolium perene L*), yorkshire fog *(Holcus lanatus L)* browntop *( Agrostis capillaries L)* and white clover *(Trifolium repens)*. Ryegrass and browntop were significantly higher ($P < 0.05$) in OP compared with WP. Clover was significantly higher in WP than OP. However, Lotus *(Lotus corniculatus L)* was only present in OP (Table 4.3). Butterup *(Ranunculus spp)* was the dominant weed present in the sward and constituted about 14 % in WP while its presence in OP was less than 5 %. The other major difference was in dead material. WP had 12 % dead material while in OP it was less than 5 %.

The spring composition was less descriptive as all the components of sward were not sorted out. However, ryegrass was significantly higher in OP than WP. Similarly weeds were also in abundance in WP compared with OP (Table 4.4). However, there were no differences in dead material.

Table 4.3 Pasture species composition (%) in early autumn 2005 in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm, near Masterton, Wairarapa.

| Treatment | Ryegrass | Browntop | Clover | Fog | Lotus | Weed | Others | Dead |
|---|---|---|---|---|---|---|---|---|
| WP | 5.2 | 16.8 | 5.3 | 24.7 | 0.0 | 13.8 | 23.3 | 12.2 |
| OP | 23.0 | 24.5 | 1.6 | 19.4 | 5.4 | 4.6 | 15.5 | 5.8 |
| SEM | | | | | | | | |
| WP | 0.4 | 3.8 | 0.6 | 2.4 | 0 | 1.2 | 1.7 | 1.2 |
| OP | 2.5 | 4.9 | 0.3 | 1.7 | 1.8 | 1.1 | 2.3 | 1.2 |
| Sig. | 0.0070 | 0.0409 | 0.0250 | 0.1493 | 0.0574 | <0.0001 | 0.0524 | 0.0237 |

Table 4.4 Pasture species composition (%) in spring 2005 in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | Ryegrass | Clover | Weed | Others | Dead |
|---|---|---|---|---|---|
| WP | 6.5 | 5.2 | 6.3 | 79.2 | 2.9 |
| OP | 24.8 | 1.3 | 1.1 | 70.8 | 1.8 |
| SEM | | | | | |
| WP | 0.4 | 0.3 | 0.6 | 2.1 | 0.5 |
| OP | 2.7 | 0.5 | 0.1 | 2.8 | 0.8 |
| Sig. | 0.0268 | 0.0453 | 0.0129 | 0.2264 | 0.7789 |

### 4.3.5 Pasture production

#### 4.3.5.1 Net herbage accumulation rate

Overall, the pasture production in WP was 52 % (5.6 t DM ha$^{-1}$ yr$^{-1}$) of the OP (10.7 t DM ha$^{-1}$ yr$^{-1}$). The mean net herbage accumulation rate was significantly higher in OP ($P < 0.05$) compared with WP (29 ± 3 kg DM ha$^{-1}$ day$^{-1}$ vs 16 ± 1.5 kg DM ha$^{-1}$ day$^{-1}$, respectively). The maximum mean daily NHA rate occurred in November in both treatments (Figure 4.2) and was significantly higher ($P < 0.05$) in OP compared with WP (68 ± 3.1 kg DM ha$^{-1}$ day$^{-1}$ vs 35.4 ± 3.3 kg DM ha$^{-1}$ day$^{-1}$, respectively). However, the minimum NHA rate occurred in July and was similar ($P > 0.05$) between OP and WP (4 ± 1.7 kg DM ha$^{-1}$ day$^{-1}$ vs 2 ± 2.7 kg DM ha$^{-1}$ day$^{-1}$, respectively). The NHA rate values were negative for some individual samples in July but overall mean values were positive for both treatments. April, May and June were the only other months with similar NHA rate ($P > 0.05$) between treatments during the trial period.

Table 4.5 summarises the seasonal herbage accumulation rate (kg DM ha$^{-1}$ day$^{-1}$). The seasonal pooled data analyses revealed that maximum herbage accumulation in OP and WP was in the spring (45 % vs 44 %, respectively) followed by the summer (34 % vs 30 %, respectively). Pasture production rapidly declined in autumn in both OP and WP and net production was 12 % and 16 % of the total production, respectively. However, the decrease in herbage rate in autumn was significantly higher in OP (66 %) than WP (48 %) compared with summer. The lesser decline in herbage accumulation rate in WP was probably because of the positive effect of shade. The winter production was small (below 10 %) in both OP and WP. Nevertheless, the herbage accumulation rate remained significantly higher in OP in spring, summer and autumn but winter production was similar between treatments (Table 4.5).

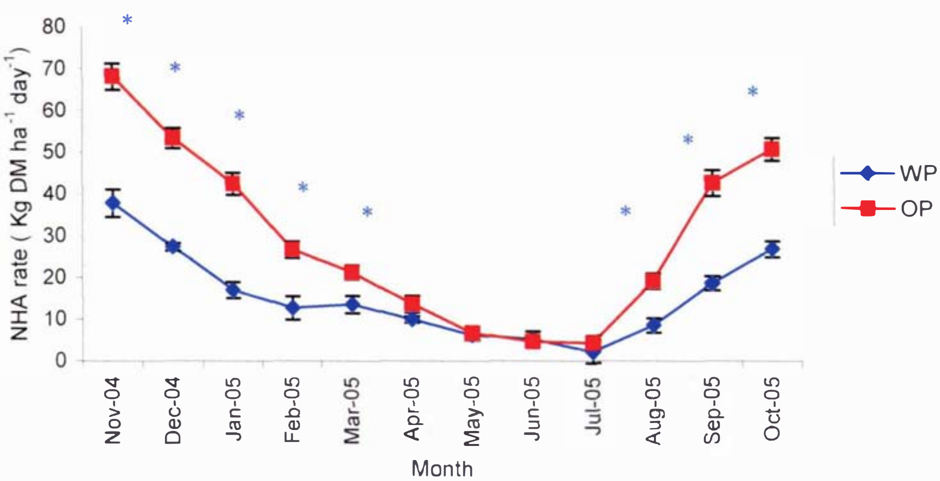


Figure 4.2 Net herbage accumulation (NHA) rate from November 2004 to October 2005 in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes a significant difference between treatments at P < 0.05.

Table 4.5 Seasonal NHA rate (kg DM ha$^{-1}$ day$^{-1}$) for 2004-05 in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | Spring | Summer | Autumn | Winter |
|---|---|---|---|---|
| OP | 54 | 41 | 14 | 9 |
| WP | 28 | 19 | 10 | 6 |
| SEM | | | | |
| OP | 3.56 | 3.51 | 1.99 | 2.24 |
| WP | 2.43 | 2.14 | 1.21 | 1.41 |
| Sig. | <0.0001 | <0.0001 | 0.0428 | 0.0524 |

#### 4.3.5.2 Cumulative herbage yield

Month wise cumulative herbage rate for WP is given in Figure 4.3. At the start of the measurement of cumulative herbage rate, there was a mean total existing pasture cover of 2.56 ± 0.10 t DM ha$^{-1}$ at the end of November 2004. The rate of cumulative herbage yield increased in spring and summer and reached to climax in February, 2005 (4.64 ± 0.25 t DM ha$^{-1}$ month$^{-1}$). However, the maximum gain in an individual month occurred in December with an increase of 0.98 t DM ha$^{-1}$ month$^{-1}$. The minimum increase in herbage yield occurred in February with a gain of 0.47 t DM ha$^{-1}$ month$^{-1}$.

During autumn and winter, the rate of cumulative herbage yield decreased with maximum fall observed in July (1.43 t DM ha$^{-1}$ month$^{-1}$) compared with a total mean herbage value of 3.24 ± 0.28 t DM ha$^{-1}$ month$^{-1}$ in the preceding month of June. The 2$^{nd}$ major fall in pasture accumulation was observed in June (0.68 t DM ha$^{-1}$ month$^{-1}$) compared with the total mean herbage cover of 3.92 ± 0.19 t DM ha$^{-1}$ month$^{-1}$ in May.

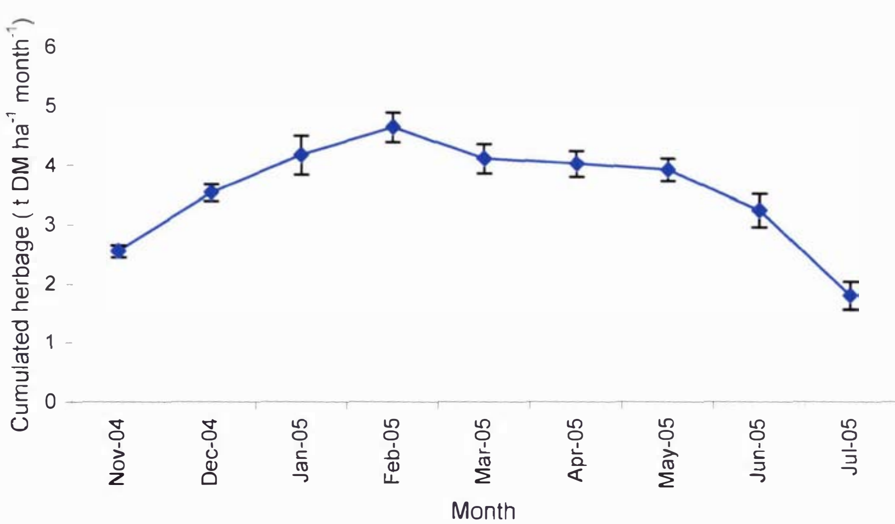


Figure 4.3 Cumulative herbage accumulation rate (kg DM ha$^{-1}$ month$^{-1}$) from November 2004 to July 2005 in willow pasture (WP) treatment at Riverside Farm near Masterton, Wairarapa. Line bars show the SEM.

### 4.3.6 Willow leaf area development.

Mean leaf area for coppice willow was small (0.05 ± 0.005 $m^2$ $tree^{-1}$) in late December, 2004 due to sheep browsing in late November compared with late December, 2005 (1.17 ± 0.22 $m^2$ $tree^{-1}$) when willow were not browsed in early summer. Leaf area increased during summer months and reached a maximum in late February in both the $1^{st}$ and $2^{nd}$ year (0.91 ± 0.11 $m^2$ $tree^{-1}$ vs 2.03 ± 0.33 $m^2$ $tree^{-1}$, respectively). Due to leaf fall, the leaf area decreased from February onward and the late April measurement proved to be the last as there was not a measurable number of leaves by the end of May. However, leaf area was significantly higher throughout the $2^{nd}$ year compared with $1^{st}$ year (Figure 4.4). Willow leaf area may have been affected by willow gall sawfly causing red lumps starting from early summer (Plate 4.1) but Orthene chemical containing 195 g $L^{-1}$ acephate was used to kill the sawfly that eats the leaves.

Plate 4. 1 Willow gall sawfly attack on Kinuyanagi willow *(S. viminalis)* leaves in willow pasture (WP) treatment at Riverside Farm near Masterton, Wairarapa.

Considering the mean canopy area of 0.28 $m^2$ $tree^{-1}$ (section 4.3.5) measured in February 2006, when the leaf area was at its peak, the maximum LAI value would be 7.25 while assuming the same canopy area in February 2005, the maximum LAI would be 3.25.

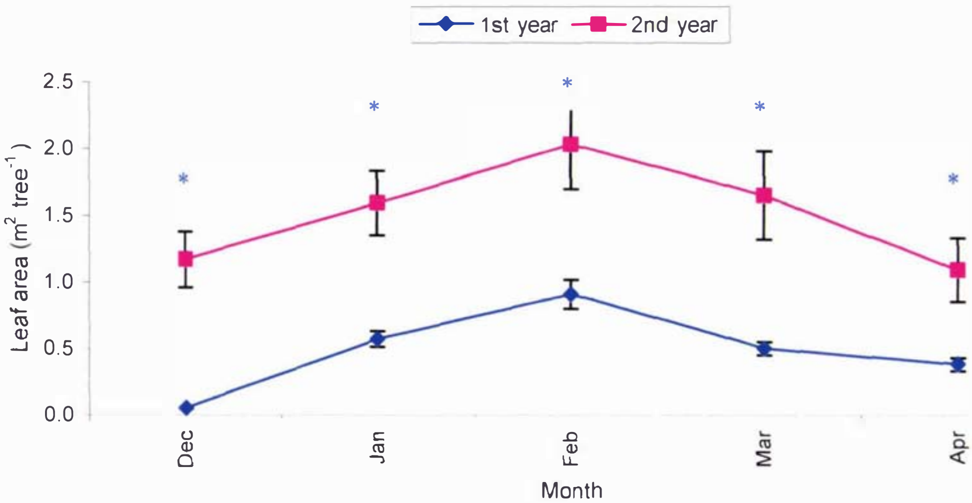


Figure 4.4 Leaf area difference ($m^2$ $tree^{-1}$) between browsed (1st year) and unbrowsed (2nd year) willow coppice trees in willow pasture (WP) treatment at Riverside Farm near Masterton, Wairarapa. Line bars show the SEM for each date. * denotes $P < 0.05$ significance.

The data for leaf area of individual trees were weakly related to NHA rate ($y = -0.958x + 0.9622$ $R^2 = 0.4109$). However, there was a strong linear relationship between overall mean monthly values for willow leaf area from December to February and understorey NHA rate (Figure 4.5). Willow leaf area was not related to the changes in soil moisture at 0-150 mm, 0-300 mm or 0-450 mm depth ($y = -0.7605x + 0.766$ $R^2 = 0.19$, $y = -0.8293x + 0.7723$ $R^2 = 0.12$, $y = -1.1667x + 0.8903$ $R^2 = 0.14$, respectively).

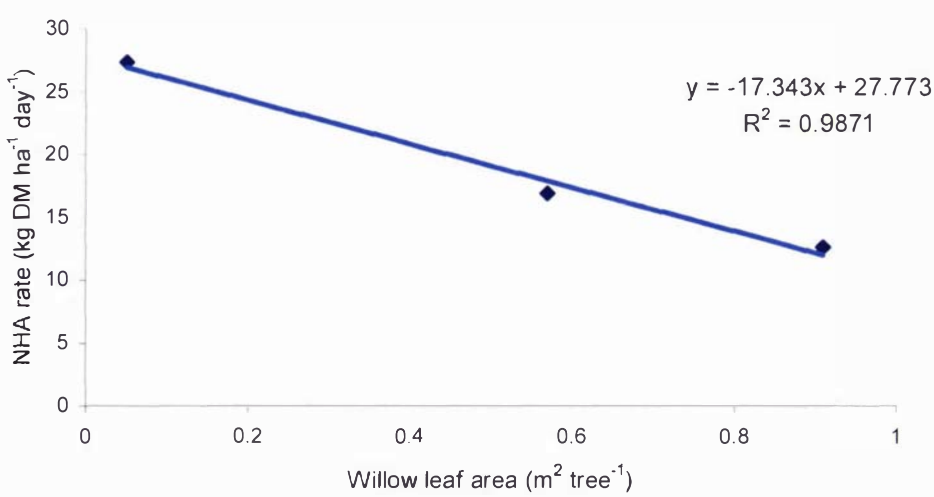


Figure 4.5 Linear relationship between willow leaf area ($m^2$ $tree^{-1}$) and understorey net herbage accumulation rate (kg DM $ha^{-1}$ $day^{-1}$) in willow pasture (WP) treatment from December to February at Riverside Farm near Masterton, Wairarapa.

## 4.3.7 Light and tree canopy

Mean photosynthetically active radiation (PAR) under the willow tree canopy with position relative to the main stem towards the edge of the canopy. The PAR level close to the main stem was 12.3 % (93.36 ± 4.57 μmoles photons $m^{-2}$ $s^{-1}$) of that of OP and increased to 21.8 % (398.57 ± 23.07 μmoles photons $m^{-2}$ $s^{-1}$) when measured between the tree stem and canopy edge. The PAR level further improved towards the edge of canopy and was 41.6 % (760.97 ± 31.29 μmoles photons $m^{-2}$ $s^{-1}$) of that of OP when measured close to the edge of the canopy.

Mean height of the willow was 2.1 m ± 0.05 and the canopy circumference was 1.89 m ± 0.07, giving a canopy closure ratio of 19.5 % between four nuclei trees.

## 4.3.8 Soil moisture content

### 4.3.8.1 0-150 mm depth

Overall there were no significant ($P > 0.05$) differences in soil moisture content between treatments over the period of the trial at the 0-150 mm depth (Table 4.6). However, soil moisture changed significantly with time in both treatments during the study period. During the first year of the experiment, soil moisture generally remained high in WP compared with OP but significant differences were restricted to a few times in summer and autumn months. For example, soil moisture was significantly higher ($P < 0.05$) in WP on 7$^{th}$ December 2004 compared with OP (45.5 ± 2.4 % vs 33.5 ± 2.7 %, respectively). During the following summer months, soil moisture declined below 15 % in both treatments and was significantly higher in WP on 8$^{th}$ February and 25$^{th}$ March 2005 (21.5 ± 0.5 % vs 18.9 ± 0.6 % and 22.9 ± 0.1% vs 20.3 ± 1.0 %), but was similar to OP on 25$^{th}$ February and 7$^{th}$ March 2005 (13.3 ± 1.5 % vs 13.3 ± 0.8% and 10.7 ± 1.0 % vs 13.5 ± 0.7 %), respectively. Conversely, soil moisture was significantly higher in OP ($P < 0.05$) on 16th September (46.6 ± 1.9 % vs 34.5 ± 2.8 %) and 13$^{th}$ December 2005 (38.6 ± 4.1 % > 25.2 ± 1.3 %) but was not consistent during the following summer and autumn months and remained similar between treatments from January to April 2006 (Figure 4.6).

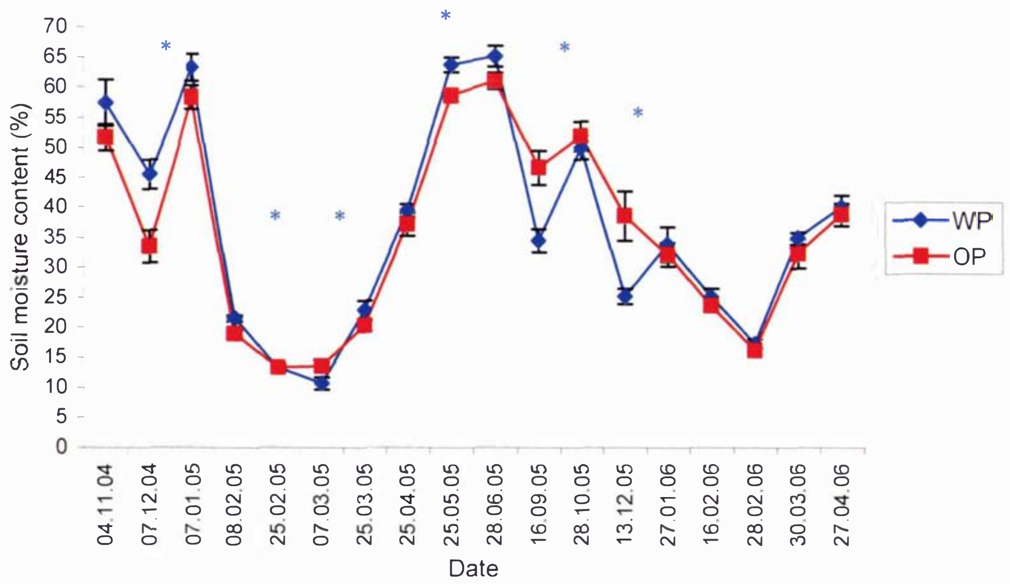


Figure 4.6 Volumetric soil moisture content (%) at 0-150 mm depth at Massey's Riverside Farm near Masterton, Wairarapa. Line bars show the SEM for each date. * denotes significance at P < 0.05.

Table 4.6 Least square means comparison for volumetric soil moisture content (%) between willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | Soil moisture content (%) at different depths (mm) | | | | |
|---|---|---|---|---|---|
| | 0-150 | 0-300 | 150-300 | 0-450 | 350-450 |
| WP | 36.9 | 35.9 | 34.9 | 35.4 | 34.3 |
| OP | 35.9 | 35.2 | 34.4 | 36.1 | 37.6 |
| SE | | | | | |
| WP | 0.61 | 0.48 | 0.58 | 0.44 | 0.91 |
| OP | 0.61 | 0.48 | 0.58 | 0.44 | 0.91 |
| Sig. | 0.2997 | 0.3204 | 0.5611 | 0.2702 | 0.0456 |

#### 4.3.8.2 0-300 mm depth

Significant differences at 0-300 soil depth were restricted to a few times during the study period (Figure 4.7). For example, soil moisture was significantly higher in WP on 7th December 2004 compared with OP (38.3 0.8 ± % vs 35.4 ± 0.7 %), respectively. The differences were again noticed in February 2005 when soil moisture was significantly higher in WP compared with OP on 8th and 25th of

February (26.4 ± 0.7 % vs 21.7 ± 0.5 and 19.9 ± 0.9 % vs 17 ± 0.5 %), respectively. Such differences were not consistent during the rest of the study period except on 16th September 2005 when soil moisture was significantly higher in OP compared with WP (42.4 ± 1.6 % vs 35.9 ± 0.7 %).

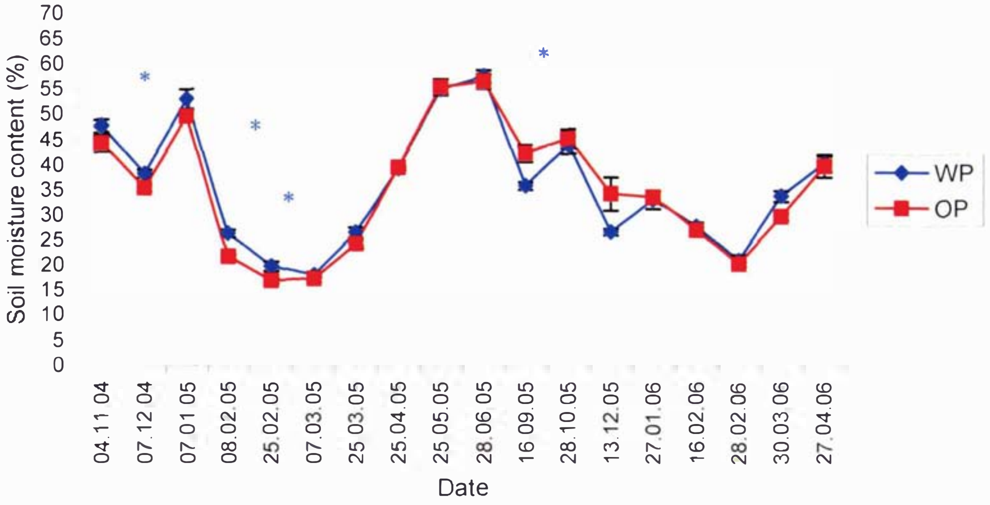


Figure 4.7 Volumetric soil moisture content (%) at 0-300 mm depth in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa. Line bars show the SEM for each date. * denotes significance at P < 0.05.

Soil volumetric moisture content (v/v %) in the 150-300 mm depth remained similar between treatments throughout the study period (Appendix 4.1). The repeated measures analysis showed similar soil moisture content between treatments over the period of trial (Table 4.6).

#### 4.3.8.4 0-450 mm depth

Soil moisture content of the 0-450 mm depth remained similar between treatments throughout the study period except on 16th September and 13th December 2005 (Figure 4.8) when soil moisture content was significantly higher in OP compared with WP (41.3 ± 1.3 % vs 36.4 ± 0.6 % and 34.5 ± 2.0 % vs 26.4 ± 0.8 %, respectively). Repeated measures analysis revealed that soil moisture content for the 0-450 mm depth was not significantly different between treatments (Table 4.6).

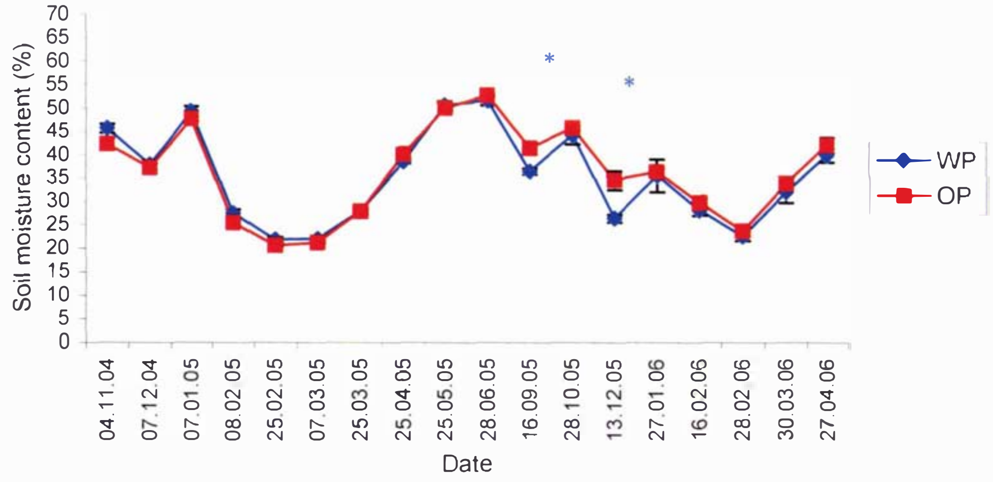


Figure 4.8 Volumetric soil moisture content (%) at 0-450 mm depth in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa. Line bars show the SEM for each date. * denotes significance at P < 0.05.

Appendix 4.2 illustrates the changes in soil moisture content at 300-450 mm depth in WP and OP for the study period. The time series analysis (repeated measures) showed that soil moisture was significantly higher in OP than WP at 300-450 mm soil stratum (Table 4.6). The significant differences in soil moisture were noted on 13$^{th}$ December 2005 for the first time when soil moisture was higher in OP than WP (35 ± 1.0 % vs 25.9 ± 1.5 %, respectively). Such differences were not noted again during the summer months and were only recorded on 27$^{th}$ April 2006 when soil moisture was again higher in OP compared with WP (46.2 ± 0.7 % vs 38.6 ± 1.6 %, respectively).

#### 4.3.8.6 Soil moisture relation with net herbage accumulation

There was no linear relationship between mean monthly herbage accumulation rate (kg DM ha$^{-1}$ month$^{-1}$) and mean monthly soil volumetric water content (%) at 0-150 mm depth and the regression analysis was not significant for either WP ($R^2$ = 0.02, P = 0.427) or OP ($R^2$ = 0.04, P = 0.295) for all the months. However, the relationship for November 2004 to March 2005 data showed stronger relationship for OP than WP (Figure 4.9). The regression analyses determined that change in soil moisture during these months affected NHA rate significantly in both WP (P = 0.007) and OP (P = <0.0001).

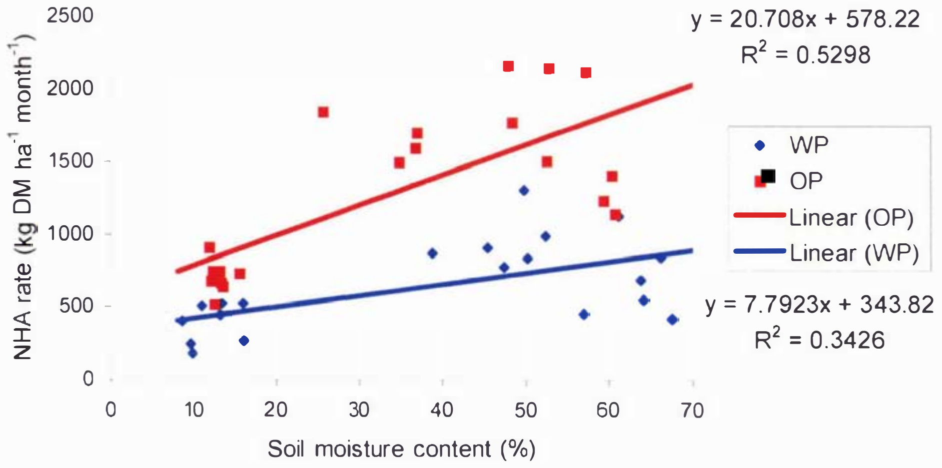


Figure 4.9 Relationship between mean monthly volumetric soil moisture content (%) in the 0-150 mm depth and NHA rate (kg DM ha$^{-1}$ month$^{-1}$) from November 2004 to March 2005 in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm near Masterton, Wairarapa.

# 4.4 Discussion

## 4.4.1 Annual and seasonal net herbage accumulation

In the present study, pasture in the willow browse block grew much less than in the open-pasture area. The total NHA in OP was 10.7 t DM $ha^{-1}$ $yr^{-1}$ compared with 5.6 t DM $ha^{-1}$ $yr^{-1}$ in WP i.e. pasture production in WP was 52 % of OP. Shading by willow trees in summer and autumn was the most prominent growth limiting factor in tree pasture area. However, lower pasture growth in WP in spring (when trees did not have many leaves to impose shade) indicated that pasture species composition was also responsible for differential growth between treatments. Soil water generally was not limiting, but during February and March 2005, water availability in the top soil was very low and affected the pasture growth equally in both treatments. Winter and spring soil water measurements illustrate the swampy characteristic of the site. The addition of urine and dung from grazing sheep in OP area might also have had some positive influence on pasture growth in this treatment.

The total pasture production of 10.7 t DM $ha^{-1}$ $yr^{-1}$ for an open pasture area at Riverside Farm, was similar to the annual DM production of 9.99 t DM $ha^{-1}$ $yr^{-1}$ reported by Ramirez-Restrepo et al., (2006) for 2001-02 from the same farm. However, smaller values were reported from the same experiment for 2000-01 and 2002-03 (7.03 t DM $ha^{-1}$ $yr^{-1}$and 7.06 t DM $ha^{-1}$ $yr^{-1}$, respectively). Similarly, Radcliffe (1975) reported mean DM production of 8.9 to 14.9 t DM $ha^{-1}$ $yr^{-1}$ over the period of five years for ryegrass, browntop and white clover pasture near Masterton (Wairarapa). The differences in pasture production between the current study and the other measurements are probably because of seasonal variations in rainfall and temperature between the years and/or sites.

The marked seasonal variations in pasture production observed in the current study with maximum production in spring (45.5 % vs 44.2 %) followed by summer (34.5 % vs 30.2 %) in OP and WP treatments were similar to those reported by Radcliffe (1975) and Ramirez-Restrepo et al., (2006) both for spring and summer. Very similar seasonal distribution of pasture production has also been reported elsewhere in New Zealand (Baars, 1975; Morton & Paterson, 1982).

Seasonal variations in pasture production were probably a function of changes in; extent of shading, soil moisture content and temperature. For example, Radcliffe (1975) stated that spring growth at Masterton was associated with slowly rising temperatures in September-October following mean daily soil temperatures around 5 $^{o}$C (at 5 cm depth) and higher rainfall in October. The very small net herbage accumulation (and even negative values for some individual samples) during winter in the current study was probably due to very low soil temperature and high soil moisture in both treatments. The optimum temperature range for pasture growth is between 18 and 25 $^{o}$C, but perennial ryegrass growth ceases below 6 $^{o}$C (Kunelius & Clark, 1970; Mitchell, 1956).

### 4.4.2 Cumulative herbage yield

The maximum increase in cumulative herbage rate during spring and early summer 4.64 t DM ha$^{-1}$ month$^{-1}$ was less than 6.0 t DM ha$^{-1}$ month$^{-1}$ measured for the Riverside Farm (Ramirez-Restrepo et al., 2006). However, the environmental conditions were not the same during both studies. Secondly, Ramirez-Restrepo et al., (2006) made measurements in open pasture while in the current study cumulative growth was monitored in a willow browse block. The decrease in cumulated herbage rate during late summer and autumn indicated that senescence surpassed the accumulation rate, thereby suggesting that pasture quality at this stage was not at its best. Pitta et al., (2006) reported from the same farm that the herbage in the willow fodder blocks was of lower quality in ME than long drought pasture in the open pasture. This was also reflected in the early autumn pasture species composition as WP had significantly more dead material than OP (Table 4.3). At a trial on fallow pasture at Ballantrae, near Woodville, Mackay et al., (1991) measured a net loss of 40 kg DM ha$^{-1}$ day$^{-1}$ by late April/May, as both grass and legume decomposed. Nearly 50 % decline in tiller densities was also reported by the end of fallow. Pastoral fallow can also affect the rooting system of pasture and soil permiability. For example, Nie et al., (1997b) reported an alteration in root growth and distribution with significantly less ($P < 0.01$) root biomass at 0-150 mm soil depth in the fallowed sward compared with open grazed pasture. A pastoral fallow, which involves no defoliation of pasture for a period generally from spring to autumn, has been suggested as a management tool to reduce plant population density of hill pasture in preparation for oversowing pasture with improved germplasm (Nie et al., 1997a).

### 4.4.3 Soil moisture relation with pasture production

The mean monthly values of soil moisture for the total period of pasture measurement were not helpful to explain the seasonal variation in the DM production, partly because of the variation in temperature over the seasons, a factor that also plays vital role in determining the rate of pasture production in conjunction with soil moisture. At the same soil moisture level, pasture production could be significantly different during winter compared with any other season. For example, in January 2005, WP and OP had an NHA rate of 16.9 ± 1.9 kg DM ha$^{-1}$ day$^{-1}$ and 42.4 ± 2.6 kg DM ha$^{-1}$ day$^{-1}$ at the soil moisture level of 63.2 ± 2.2 % and 58.3 ± 1.9 % (0-150 mm depth) but the NHA rate reduced to only 5.1 ± 1.9 kg DM ha$^{-1}$ day$^{-1}$ and 4.5 ± 1.0 kg DM ha$^{-1}$ day$^{-1}$ in June 2005 at roughly the same moisture level (65.1 ± 1.7 % vs 61 ± 1.3 %) in WP and OP, respectively. Similarly, at relatively low level of soil moisture (57.4 ± 3.8 % vs 51.7 ± 2.2 %), NHA rate was even higher (37.8 ± 3.3 kg DM ha$^{-1}$ day$^{-1}$ vs 68.1 ± 3.1 kg DM ha$^{-1}$ day$^{-1}$) in November 2004 than January 2005 in WP and OP, respectively. This explains that even at quite high levels of soil moisture, NHA rate can be limited by low temperature, as in June, but at appropriate temperatures in November 2004, NHA rate can be even higher (nearly double) than for the high level of temperature in January, 2006.

Soil moisture mainly remained higher in WP than OP during the pasture measurement period. This was despite a continuous increase in willow leaf area during summer (Figure 4.4). This indicated that WP site was wetter overall than OP. During winter and early spring, WP site was presenting a waterlogged situation. That is why moisture measurements were not made in July and August 2005. Also, due to uneven surface of individual WP plots, some surface water ponding was observed in some parts of these plots during the study period, especially after rainfall. Probably this was further enhanced due to continuous pasture accumulation in the WP as whole plots were not mowed and soil moisture was being conserved due to obstruction in the water movement by cumulative pasture growth and addition of litter on the soil surface. This was later reflected in the month of January and February 2006, when despite similar soil moisture in the OP and WP, runoff was only observed in OP plots (chapter 5).

Excessive soil moisture could be detrimental for plant growth. For example, Eccles et al., (1990) reported that during waterlogging, the rate of leaf extension (mm tiller$^{-1}$ day$^{-1}$) of Matua prairie grass decreased, senescence rate (mm tiller$^{-1}$ day$^{-1}$) increased, and percentage of total dead weight increased. It was further reported that the root: shoot ratio of ryegrass decreased as a result of waterlogging. Similarly, Mwebaze (1986) reported that high soil moisture levels reduced soil oxygen levels and root and tiller production.

There was a good relationship between soil moisture content at 0-150 mm depth and leaf area (Figure 4.4) from December to February for 2004-2005 and 2005-2006. In the first year, soil moisture, especially in 0-150 mm depth, was generally higher in the willow block and this trend even persisted in late spring and summer months. However, in the second year this trend was somewhat reversed with lower or similar soil moisture in WP compared with OP (Figure 4.6). The ability of willow to affect soil moisture may have been affected by sheep browsing in the first year. But, on the other hand, browsing may have benefited the understorey pasture growth by reducing the shade effect. Therefore, the impact and implications of browsing should be taken into consideration while managing these willow browse blocks.

### 4.4.4 Light (PAR), canopy and pasture production

The understorey pasture is directly affected by the amount and quality of light filtrated through the tree canopy (Wilson & Ludlow, 1991). As sunlight passes through the tree canopy, its quality is altered because the leaves preferentially absorb the light in the 400-700 mm waveband. Blue and red light are reduced compared with green and far-red (Holmes, 1981). The ratio of red to far-red falls due to their differential absorption. These spectral changes may induce morphogenetic changes in plants (Smith, 1982) resulting in stem elongation (Child et al., 1981) and tillering and branching inhibition (Casal, 1988; Thompson & Harper, 1988 ). Work with *Pinus radiata* seedlings under a controlled environment (Warrington et al., 1988) indicated that the effect on stem elongation could be over and above that due to reduced light alone. However, this effect could be more pronounced in shade-intolerant species than shade-tolerant species (Smith, 1982).

Reduced infrared radiation in the tree pasture system has a great influence on the soil moisture-temperature complex, while decreased photosynthetically active radiation can modify the plant community and decrease growth (Guevara-Escobar, 1999). In the current study, the shade level close to the main stem was very heavy (12.3 % PAR) compared with OP and though it improved towards the canopy edge of the tree, still showed heavy shade between the canopy edge and tree stem (21.8 % PAR). The shade level just underneath the canopy edge was of medium level (41.6 % PAR). Guevara-Escober (1999) reported that daily average PAR directly under a poplar canopy in the poplar-pasture area ranged from 10 % to 60 % of the incoming radiation for open pasture.

Tree age, stand density and type of tree species also influence the understorey pasture production. Silva-Pando et al., (2002) in their study on understorey pasture production in a silvopastoral system reported that the effect of shade under *Pinus pinaster Ait* was higher than under *Pinus sylvestris L.* corresponding to 36-57 % and 16-21 % of full sunlight, respectively, despite trees being the same age. The authors obtained a significant correlation between annual pasture production and light transmission through the tree canopy ($R^2$ = 0.96, $P < 0.05$). Peri et al., (2005) studied the effect of different light regimes on understorey pasture involving P*inus radiata* trees and reported significant differences in DM. Foale et al., (1994) indicated that the shape of the tree crown and its ability to intercept light goes through a distinct series of changes with age of the tree. However, "light transmission of a canopy varies with the proportion of direct to diffuse light. Diffuse light penetrates better than direct light because it emanates from the whole hemisphere of the sky rather than from the point source of the sun. Therefore, measurements taken on a clear day will underestimate transmission of light under the trees" (Wilson & Ludlow, 1991).

In the current study, however, It can be expected that shade level was even lower in the centre of the four nuclei trees. According to Devkota (2000), the pasture growth at medium level shade should have been about 70 % of that of OP or light shade but the pasture production in the present study was only 52 % in WP (5.6 t DM $ha^{-1}$ $yr^{-1}$) of that of OP (10.7 t DM $ha^{-1}$ $yr^{-1}$). Since pasture measurements were not made directly under the canopy, the pasture production was expected to be even better away from the tree crown as a tree's influence on understorey pasture decreases with greater distance from the base of its stem (Benge, 1987; Clements et al., 1988; Gilchrist et al., 1993). However, this relationship also depends on the size and proximity of the surrounding trees (Sibbald et al., 1991). Due to close proximity (1.2 m × 1.2 m) and substantial height of surrounding trees (2 m) in the current study, the canopy gap between four nuclei trees was within the reach of tree shade and this was expected to influence pasture growth during summer and early autumn. Nevertheless, in the current study, pasture production in WP was low even during the months when there were no leaves on the trees (Figure 4.2) and only leafless coppiced stumps were visible. This shows that there were other factors involved in WP that limited the pasture growth rather than the shade alone, such as the pasture species composition.

Tree canopy closure ratio (19.5 %) between four nuclei trees was also not fully helpful to explain the mean annual NHA rate in the WP treatment. According to Wall (2006), pasture production in the centre of four nuclei trees (Zone 3) should decrease by 6.6 % with every 10 % increase in canopy closure compared with open pasture. By this estimation, the pasture production in WP should have been reduced by about 12 % compared with OP. However, pasture production can vary under different tree species for a given canopy closure ratio. For example, Guevara-Escober (1999) reported 60 % pasture production in poplar pasture than that of open pasture under 70 % measured canopy closure ratio from Pohangina valley, New Zealand. Canopy closure, expressed as the ratio of projected tree canopy to ground area covered, has been used to estimate pasture production in *Pinus radiata* silvopastoral systems by Knowles, et al.(1997). Their model predicted 0 % pasture production (relative to open pasture production) at around 70 % of *Pinus radiata* canopy closure ($R^2$ = 0.89). Canopy structure has also been related to understorey productivity as a function of stand age and tree density (Sibbald et al., 1994). Nevertheless, it is important to realise that 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).

### 4.4.5 Sheep grazing and pasture growth

In the current study, the OP plots were rotationally grazed throughout the trial period and this perhaps also had a positive bearing on pasture growth, especially in spring. Livestock grazing of pasture can have an important influence on sward composition, sward quality and herbage production (da Silva et al., 1993; Matthew, 1992). Mathew et al., (1988) observed change in pasture species composition as a result of grazing from *Hordeum jubatum* dominance at high P through *Lolium perenne* dominance at intermediate P to a *Trifolium repens/Anthoxanthum odoratum* mixture at low P. The authors reported a change in seasonal production of pasture with high fertility that was attributed to a change in species dominance with increased N input from dung and urine. Dale (1961) also reported positive effects of urine on sward growth in annular growth zone with most useful responses occurring in spring and autumn. Similarly, Thomas et al., (1988) reported a 3-fold increase in herbage mass due to urine application. Peri, et al., (2002) also reported enhanced pasture production for urine patches compared with control. It was also reported that the duration of the response to a urine patch in winter is much longer (133 days) than spring (105 days) and summer (77 days). Also, pasture production can significantly increase due to addition of nutrients from animal dung (Williams & Haynes, 1995). Zhang et al., (2001) reported a significant increase in herbage accumulation of established pasture due to sheep urine and dung effect. Similarly, Xia et al., (1990) reported a high tiller appearance and enhanced net leaf production over the summer in ryegrass pasture due to late spring grazing.

Perennial ryegrass can exhibit sufficient phenotypic plasticity to survive under intense grazing and can produce greater flowering compared to other species like Kara and Apanui cocksfoot (Brock et al., 1996). This characteristic of persistence under grazing and greater flowering in ryegrass can contribute to greater herbage mass in growing seasons such as spring and early summer. For example, Brock & Fletcher (1993) reported that during the reproductive period (late spring/early summer) ryegrass plants were heavier with more leaves and internode stolon than at other times of the year. The evidence from reviewed literature, therefore, suggests that with significantly higher proportion of ryegrass (Tables 4.3, 4.4), pasture growth may have benefited from sheep dung and urine patches in the OP compared with WP.

### 4.4.6 Species composition and herbage accumulation

In the current study, open pasture area had significantly higher proportion of ryegrass and browntop compared with willow block while the reverse was true for white clover (Table 4.3, 4.4). The lower proportion of ryegrass under trees could be due to its inability to tolerate shade (Devkota et al., 1998). Ong & Marshall (1979) also demonstrated that ryegrass did not perform well when grown under severe shade due to reduced tillering ability. However, under moderate shade, ryegrass has the ability to produce superior shoot yield compared to some other species such as *Dactylis glomerata* (a shade tolerant species) (Devkota et al., 1997). Nevertheless, some pasture species can have two different ecotypes with different responses to shade levels (Thompson, 1993). Therefore, enhancement of ryegrass in a silvopastoral system such as willow browse blocks will depend on the grazing management.

Significant higher ryegrass quantity in OP could have a positive effect on sward growth in spring. For example, Lambert et al., (1986) reported that ryegrass has maximum growth rate in spring unlike most low fertility adapted grasses that produce maximum growth in late spring to early summer. In the current study, there was no considerable tree shade in spring in the willow block but pasture growth was not to a comparable level to that of open pasture suggesting that differential pasture botanical composition, especially ryegrass, might have contributed to increased growth in open pasture area.

### 4.4.7 Willow leaf area and herbage accumulation

Willow leaf area increased in spring and summer and reached its maximum in February and declined over autumn with few leaves on trees by the end of May. The leaf area development in spring and summer was as a result of emergence of new foliage and increase in the size of existing leaves. This also affected the shoot length and tree height indicating the effect of climate on growth. Leaf area development was mainly a function of increasing temperature with adequate soil water. Whitehead (1995) reported that needle elongation in *Pinus radiata* was related to thermal time, using growing degree days with a base temperature of 6 °C at Don plantation New Zealand. Similar trends in leaf area development in willow coppice and its impact on canopy energy flux for different seasons has been discussed elsewhere (Iritz & Lindroth, 1996).

The significant difference in leaf area development between the 1st and 2nd years (Figure 4.4) highlights the importance and implications of sheep browsing in late spring in a willow browse block under New Zealand conditions. This also indicates that overstorey tree leaf area can be modified with livestock browsing in a silvopastoral system. Leaf area modification can affect tree growth and its competition with understorey pasture because productivity depends primarily on leaf area and photosynthetic rates, and tree-atmosphere exchanges of energy and water occur at the leaf level.

Tree leaf area is generally proportional to the cross-sectional area of sapwood (Marshall & Waring, 1986). Grace & Fownes (1998) reported that leaf area of *Acacia koa* trees correlated well with stem diameter (DBH) and sapwood area ($r^2$ = 0.91, $r^2$ = 0.92), respectively. Osada (2006) has shown a positive effect of previous-year leaf area on the current-year stem mass in *Rhus tricocarpa* tree. However, stem growth may cease 2-3 weeks after leaf area reaches a maximum in willow coppice (Lindroth et al., 1994).

In the current study, leaf area (during development phase) was strongly negatively correlated (Figure 4.5) to NHA rate. Bergez et al., (1997) reported that the amount of light intercepted (PAR) in the tree canopy was highly correlated with the leaf area of the tree and more importantly the rate of interception was found to be higher on brighter days compared with cloudy days. Silva-Pando et al., (2002) reported a negative relationship between tree LAI and annual herbage accumulation ($r^2$ = 0.72). These authors reported herbage accumulation of 4 t $ha^{-1}$ $yr^{-1}$ under LAI of 3.5 while in the current study pasture production was 5.6 t $ha^{-1}$ $yr^{-1}$ under LAI of 3.2. The differences could be due to other factors such as climate and pasture species botanical composition. In the current study, mean LAI of 7.2 in the 2$^{nd}$ year shows that pasture production could have been further minimised without sheep browsing. This implies that periodic sheep browsing can be used as a management tool to offset the shade effect on understorey pasture in willow browse blocks.

# 4.5 Conclusions

The total NHA rate for OP was 10.7 t DM ha$^{-1}$ year$^{-1}$ compared with 5.6 t DM ha$^{-1}$ year$^{-1}$ for WP. The mean daily net herbage rates were 29.3 kg DM ha$^{-1}$ day$^{-1}$ and 15.4 kg DM ha$^{-1}$ day$^{-1}$ for OP and WP, respectively. The maximum NHA rates occurred in November (68.1 kg DM ha$^{-1}$ day$^{-1}$ for OP vs 37.8 kg DM ha$^{-1}$ day$^{-1}$ for WP) while minimum rates were measured in July (4.2 kg DM ha$^{-1}$ day$^{-1}$ for OP vs 2.1 kg DM ha$^{-1}$ day$^{-1}$ for WP).

Maximum NHA occurred in spring (45.5 % vs 44.2 %) followed by summer herbage rate (34.6 % vs 30.2 % of total annual NHA) in both OP and WP, respectively. Winter production was the least (<10 %) in both treatments. Spring, summer and autumn pasture productions were significantly higher in OP while winter production remained similar between treatments.

The cumulative pasture yield in WP reached a maximum of 4.6 t DM ha$^{-1}$ month$^{-1}$ in February. Pasture accumulation increased during spring and summer with maximum gain in December (0.98 t DM ha$^{-1}$ month$^{-1}$). Senescence surpassed accumulation rate in autumn and winter with maximum decrease in July (1.43 t DM ha$^{-1}$ month$^{-1}$).

The main grass species constituting the sward were ryegrass, browntop and Yorkshire fog. Ryegrass and browntop were significantly higher in OP than WP. Clover was significantly higher in WP but lotus was only present in OP.

Willow leaf area development was significantly different between the 1$^{st}$ and 2$^{nd}$ years due to sheep browsing in late November in the 1$^{st}$ year. Leaf area increased during the summer months and reached to maximum in late February in both the 1$^{st}$ and 2$^{nd}$ years (0.91 m$^2$ tree$^{-1}$ vs 2.03 m$^2$ tree$^{-1}$, respectively). The maximum LAI in the 1$^{st}$ year was 3.25 while in the 2$^{nd}$ year, the maximum LAI was 7.25. Leaf defoliation was complete by the end of May in both years. Willow gall sawfly attack was observed during summer and persisted through autumn. The sawfly affected the leaf area development.

Willow gained a mean maximum height of 2.1 m and canopy circumference of 1.89 m. This corresponded to 19.5 % canopy closure ratio between four nuclei trees. PAR level varied under the willow tree canopy. The mean PAR close to the stem was 12.3 % while between stem and canopy edge, PAR was 21.8 % of that of open pasture. Maximum PAR was close to the edge of the canopy (41.6 %) compared with open pasture.

Soil moisture content generally remained higher in WP than OP in 0-150 and 0-130 mm depth during 1$^{st}$ year. However, during summer 2006, the soil moisture content was significantly higher in OP than WP. Soil moisture dropped below wilting point (<15 %) in February and March 2005.

Tree shade was the major factor affecting the understorey pasture in WP. However, pasture species composition and the addition of dung and urine by sheep grazing also enhanced the pasture growth in OP compared with WP. Sheep browsing can modify the tree leaf area that may affect the tree shade and tree ability to dry out the wet land.

## 4.6 References

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Chapter 5

# EFFECTS OF DENSELY PLANTED WILLOW AND POPLAR ON RUNOFF, SEDIMENT AND NUTRIENT LOSSES

**Table of Contents**

## 5.1 Introduction

Willow and poplar are integral part of the pastoral landscape of hill country, New Zealand. Their easy establishment and fast growth along with reasonable palatability offer a cost effective enterprise and viable option to New Zealand farmers. However, the main purpose of planting willow and poplar resides in healing the scars of soil erosion still visible on the face of hills of New Zealand, and preventing fresh erosion on hills.

In New Zealand, agricultural land has been identified as a major source of sediment and nutrient enrichment of surface runoff water (Smith et al., 1993; Vant, 1999). Stream habitat can be degraded due to increased sediment load in the runoff (Ryan, 1991). Forestry operations, especially clear felling can contribute to increased organic content in runoff sediment that undergo anerobic breakdown using dissolved oxygen during further decomposition and can cause critical oxygen shortage in the stream. For example, Graynoth, (1979) reported a fish kill in the Motueka river attributed to forestry operations in the Golden Downs State Forest, Nelson, New Zealand.

The N and P fertilisers such as urea and single superphosphate are used on pastoral lands to maintain the fertility of the soil and help increase the pasture production. While application of these fertilisers may help provide increased pasture, environmental consequences can be detrimental (Ledgard et al., 1999; Nash & Halliwell, 1999; Sharpley & Syers, 1979).

Livestock grazing on pastoral lands can affect soil physical and chemical properties by treading and deposition of excreta. Treading can cause direct plant damage and plant burial (Cluzeau et al., 1992; Drewry et al., 1999) and alter soil physical properties (Drewry et al., 2000; Drewry & Paton, 2005), at least on a temporary bases. Animal dung and urine are also implicated to be linked with increased N and P concentrations in surface runoff and drainage water (de Klein & Ledgard, 2001; Houlbrooke et al., 2003).

There have been only a few studies of the effect of trees on stream hydrology and chemistry in New Zealand (Cooper et al., 1987; Cooper & Thomsen, 1988;

McColl et al., 1977; Quinn & Stroud, 2002). These studies reported the effectiveness of trees in reducing the sediment load and improving the water quality, vital for minimising the eutrophication of streams and rivers of New Zealand. However, the ability of willow and poplar to reduce surface runoff and sediment and nutrient loss has never been measured. This prompted the conducting of field trials to test the effectiveness of young willow and poplar (< 5 yrs) trees in a silvopastoral system. Therefore, the objectives of these experiments included:

(i) Study the effect of willow and poplar on soil moisture at different depths (0-150 mm, 0-300 mm and 0-450 mm).

(ii) Determine the effect of poplar and willow trees (< 5 yrs) on surface runoff.

(iii) Measure the sediment losses in runoff water

(iv) Quantify the N and P losses in surface runoff and drainage

(v) Study the effect of sheep grazing and fertiliser application events on sediment and nutrient losses

# 5.2 Materials and methods

## 5.2.1 Site description

The Moginie experiment was conducted on a previously established site (Sulaiman, 2006) at the 'Pasture and Crop Research Unit' Moginie, Massey University, Palmerston North. The willow (Tangoio) and poplar (Veronese) were established in September 2002 using 60 cm long stakes of 25 mm diameter in a square grid at 1.2 m spacing in six rows thereby giving 36 trees in each plot. The stakes were driven 30 cm into ground leaving 30 cm above ground. The site is located $175^{o}$ 37 E and $40^{o}$ 21 S longitude and latitude, respectively, at 30 m altitude from sea level with an average annual rainfall of approximately 1000 mm. The water movement in the subsoil is not uniform due to preferential flow to mole channels in the cracks generated during mole ploughing (Scotter et al., 1979a).

The soil is classified as an Argillic-fragic Perch-gley (Hewitt, 1998) derived from deep deposits of loess-blown river sediments which form on a deeply dissected uplifted marine terrace (Molloy, 1998). The soil consists of a weakly to moderately developed, brown, silt loam A-Horizon (c. 0–250 mm soil depth), a weakly developed, grey, strongly mottled, clay loam B-Horizon (c. 250– 800 mm soil depth) and a highly compacted, weakly developed, pale-grey, silt loam fragipan C-Horizon, which acts as a natural barrier to drainage (Scotter et al., 1979a)

Due to its poor internal drainage, Tokomaru silt loam is subjected to water logging in winter and early spring (Hudson et al., 1962). However, in summer and early autumn, pastures usually experience a period of growth-limiting water stress (Scotter et al., 1979a). The other characteristics include the bulk density of 1.1 Mg $m^{-3}$, a saturated hydraulic conductivity of 32 mm $day^{-1}$, and a field capacity value of 45 % v/v for the 0–100 mm depth (Scotter et al., 1979a).

The site description for the Riverside Farm experiment has been given in chapter 4 section 4.2.1.

### 5.2.2 Experimental design and treatments

At Moginie, plots were selected that had poplar (Veronese) and willow (Tangoio) trees originating from stem cuttings planted at 1.2 m spacing in September 2002 (Sulaiman 2006) while the pasture plots were selected for their close proximity and were cleared of any non-pasture species etc. The experiment was a randomised complete block (RCB) design with two blocks and two treatments, namely: Tree Pasture (TP) and Open Pasture (OP). TP had four replicates (willow and poplar each represented two replicates) while OP had two replicates. Although slope varied between individual plots and tended to be steeper in TP, it was not statistically different between OP and TP (4.6 ± 0.22 % vs 5.7 ± 0.40 %, respectively). Both TP and OP were grazed with sheep in December 2005, June 2006 and November 2006 to study the sheep camping behaviour and grazing impact on runoff and drainage water quality.

The experimental design for Riverside Farm has been described in section 4.2.2. However, due to financial constraints, only two plots were developed for runoff measurement in each treatment (WP and OP). The slope in WP and OP plots was similar (6.3 ± 0.21 % vs 5.9 ± 0.36 %, respectively). WP plots were grazed with sheep before the set up of plots for runoff measurement but OP plots were grazed rotationally through out the period of trial.

### 5.2.3 Soil sampling and laboratory analyses

At Moginie experimental site, soil samples were collected at the start of the experiment and laboratory analyses for Olsen P were conducted using the same procedure and methodology described in section 3.2.4. The procedures for soil sampling and analyses for the Riverside Farm experiment have been given in section 4.2.3.

### 5.2.4 Soil moisture measurement

The soil moisture content was measured using the same methodology described in section 3.2.5. A single set of probes was inserted at 0-150 mm, 0-300 mm and 0-450 mm depth in the middle of each plot at 250 mm distance from trees. The soil moisture content for the 150-300 mm and 300-450 mm soil depths were obtained using the same equation described in section 3.2.5.

### 5.2.5 Plots setup and runoff instrumentation

In order to capture surface runoff, the plots required borders capable of preventing incoming surface water from the surrounding area entering the plots and vice versa. It also required a system that could discharge the surface water from the plot to a single outlet where volume and flow rate could be measured accurately.

Plots (6 m × 6 m) at Moginie and (9 m × 4.5 m) at Riverside Farm were marked using string. Channels (80 mm deep) were excavated along the marked lines on three sides (top, right and left) of each plot. A wooden board was driven into each channel to demarcate the plots and prevent outside water entering into the plots. The excavated soil was repacked along the wooden boards to prevent water accumulation on either side.

At the bottom end of each plot a trench was excavated so as to fit a length of PVC spouting. The PVC spouting was placed at right angles to the slope and set into the ground to be level with the down slope soil surface (Plate 5.2b). A 60 mm wide galvanised metal sheet was prepared to fit the plot width and folded giving 40 mm and 20 mm edges. The sheet was placed along the soil face with the 40 mm edge facing upslope and driven 20 mm into the upslope soil face at a depth of 10 mm from soil surface. The 10 mm exposed soil face above the sheet was sealed using silicon sealant to stabilise soil and prevent soil erosion during a rain event. The other 20 mm edge of the sheet was dropped over the spouting allowing water to drop directly into the spouting without any loss or leakage.

A wooden board was fixed along the length of the other side of the spouting to further strengthen the spouting and stabilise against any movement that could have been created by the surface runoff water. To this buried board another wooden board (200 mm × 25 mm) was nailed to provide a cover over the spouting to prevent rainfall water entering directly into the spouting. The other edge of the covering board was nailed to wooden pegs driven into the ground.

Outside the bottom end of each plot (1.5 m from plot boundary), soil was excavated to create a pit (1 m × 1 m × 0.75 m). Each pit was lined with galvanised roofing sheets, nailed to wooden pegs in each corner of the pit, to prevent soil being dropping into the pit from side walls (Plate 5.1a, b). A heavy cement slab (60 cm × 48 cm × 6.5 cm) was fixed at the bottom of each pit. Each slab had bolts that allowed adjustment to level the tipping bucket. The floor around the slab was lined with gravel.

Two-litre tipping buckets were constructed from PVC sheets. Each tipping bucket was fixed onto a metal frame (56 cm × 32 cm × 53 cm) that was mounted on the cemented slab in each pit (Plate 5.1b). The runoff water was directed from spouting to each tipping bucket via down-pipe (80 mm external diameter). A short length of PVC pipe (21.5 mm external diameter) with a 10 mm slot was mounted at the base of one side of the frame of the tipping bucket to catch a small sample of the water from each tip of the bucket. The sub sample was fed into a five litre container via a short length of garden hose (15 mm external diameter). The 10 mm diameter slot gave 0.4% sample of the total runoff volume. A data logger was fixed to each tipping bucket to count the number of tips (Plate 5.1b). Each tipping bucket was covered with a ply wood lid to prevent rain water dropping into the tipping bucket. A subsurface drain (110 mm external dia) was installed to conduct the water away from the bottom of the pit (Plate 5.2a).

(a) (b)

Plate 5.1 (a) View of a tree pasture (TP) plot showing plot borders with wooden boards, down pipe and pit during setup for runoff measurement at Moginie, Manawatu. (b) View of a tipping bucket fixed in a frame and mounted on a slab in the pit at Moginie, Manawatu.

Each tipping bucket was individually calibrated for static and varying flow rates. Dynamic calibration was developed inside the laboratory for each tipping bucket to provide a measure of runoff flow rates taking into account the spillage. This was done by measuring the change in tip volume over a range of flow rates, which was in turn used to develop a relationship between tipping rate and volume per tip. Data loggers connected to the tipping buckets in the field provided a record of tipping rates and dynamic calibration was then used to determine tip volume.

Static calibration was done in the field after fixing the tipping buckets in each pit. Water was poured with a ten litre pail slowly and carefully not to exceed the tipping bucket handling capacity. Pouring of water was stopped when the bucket started to tip. The volume of water required to initiate a tip was calculated by weighing the ten litre pail before and after pouring with a digital scale. The process was repeated ten times and the average volume that triggered a tip was calculated for each bucket.

(a)

(b)

Plate 5.2 (a) Trench excavated to discharge surplus water from the main pit at Riverside Farm. Novaflow pipe is ready to be laid into the trench. (b) Spouting laid into the trench at the bottom end of a tree pasture (TP) plot at Moginie, Manawatu.

### 5.2.7 Drainage instrumentation.

Suction cups (Eriksen et al., 2004) at 0-300 mm depth were used to sample soil water at the Moginie site. A suction of approximately 80 KPa was applied to create a vacuum 24 hours prior to sampling. The samples were collected using a syringe attached to a silicon tube long enough to reach to the bottom of the suction cup.

### 5.2.6 Runoff and drainage sampling and laboratory procedure

Surface runoff from plots was measured event wise as and when they happened. The sample collected in the five litre container was shaken and then poured into a graduated plastic jug. The total sample volume was noted for each plot for each event. This provided a back up information on runoff in case of data logger failure. The samples for chemical analysis of nutrients were collected in a 120 ml plastic container. In case of small events where 120 ml sample volume was not available, the whole available sample was collected. Samples were transported to Massey University, Palmerston North and frozen until analysed. The sediment samples were collected from larger events, preferably those events with a minimum of 500 ml of sediment sample. However, at times, small size samples were also used for important events such as those used to study grazing and vegetative cover effects.

Water quality analyses were conducted on runoff and drainage samples. However, runoff events with insufficient sample volume were not analysed. The runoff analysis included: suspended solids (SS), total phosphorus (TP), dissolved reactive phosphorus (DRP), total kjeldahl nitrogen (TKN), nitrate-N ($NO_3^-$-N) and ammonium-N ($NH_4^+$-N). Total nitrogen was calculated by adding $NO_3^-$-N values to that of TKN. The drainage samples were only analysed for DRP, $NO_3^-$-N and $NH_4^+$-N. Analyses were conducted colorimetrically on a Technicon II Auto Analyser. Individual nutrient and sediment analyses were carried out using the methods given below:

(i) $NH_4^+$-N was determined by the method of Searle (1975).

(ii) $NO_3^-$-N was determined by the method of kemphake et al., (1967) using a hydrazine reduction.

(iii) TKN following acid digest by the method of McKenzie & Wallace (1954).

(iv) DRP by the method of Murphy & Riley (1962).

(v) TP was determined by the vanadomolybdate method (AOAC, 1975) following a Kjeldhal acid digest as described by McKenzie & Wallace (1954).

(vi) Suspended solids were determined gravimetrically. Samples were filtered through Whatman GF/C filters. After filtration, filters were dried for 24 hours at 105 $^{o}$C. The residue was weighed in an analytical balance to calculate the total concentration of suspended solids. The organic content of the suspended solids was estimated as the loss weight after ignition at 550 $^{o}$C for four hours (APHA., 1980).

### 5.2.7 Simulated rainfall

Simulated rainfall was used at the Moginie site in autumn 2006. Galvanised iron pipes (GI) were fixed to posts in each corner of the plot while a 5$^{th}$ pipe was fixed to a post in the centre of the plot. The pipes were connected with garden hose pipes each supplying water from the main pipe. At the top of each GI pipe, a sprinkler was fixed. Each sprinkler had an adjustable nozzle to spray water in a desired direction. The drop size was also adjustable. The corner sprinklers were set to 90$^{o}$ inward while the central sprinkler was adjusted to 360$^{o}$ to spray water all around the plot. The water was supplied from a single main on-farm water source from a height of 5.6 m in OP and TP (just above the trees) plots. The intensity of the simulated rainfall (mm h$^{-1}$) and its distribution in the plots were measured by placing plastic buckets at even space in the plot. Plots were irrigated during very calm periods to avoid wind effects.

## 5.3 Results (Moginie experiment)

### 5.3.1 Olsen P

The mean soil Olsen P in the 0-75 mm and 75-150 mm soil depths were 36 µg $g^{-1}$ and 17 µg $g^{-1}$, respectively. The soil pHs for the 0-75 mm and 75-150 mm depths were similar (5.3), respectively. However, Olsen P and pHs were not significantly different between treatments (P > 0.05).

### 5.3.2 Rainfall and temperature

The monthly rainfall prior to April 2006 has been given in Figure 3.2 while rainfall for the subsequent months is given in Figure 5.1. In October 2006, the rainfall was more (172 mm) than in any other individual month since April 2006 while September 2006 yielded the least rainfall (69.2 mm). Overall, spring rainfall was more (373.8 mm) than winter rainfall (352.6 mm). The smallest mean minimum air temperature (2 °C) was recorded in June 2006 while the greatest mean maximum air temperature (20 °C) was in April 2006 (Figure 5.1).

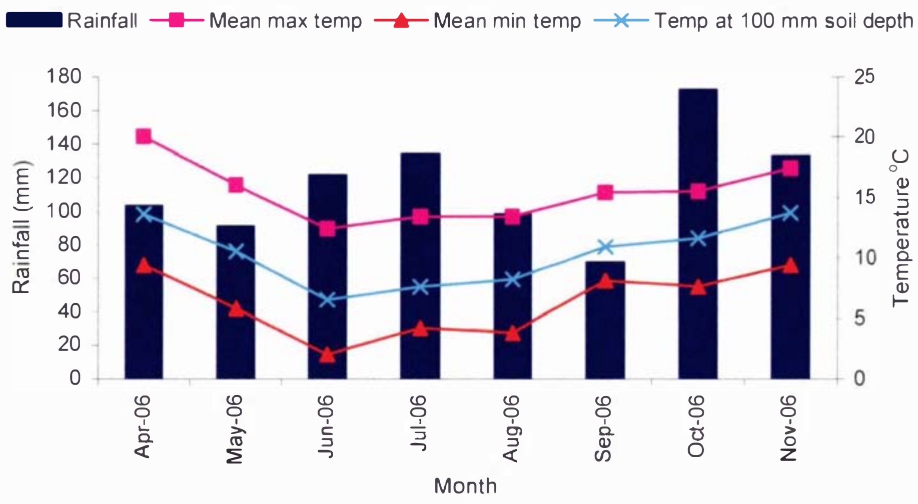


Figure 5.1 Total monthly rainfall (mm) and mean air and soil temperature (°C) during the experimental period in Palmerston North, New Zealand.

(Source: AgResearch)

## 5.3.3 Soil moisture content

### 5.3.3.1 0-150 mm depth

In winter 2005, soil moisture content to a depth of 150 mm was close to field capacity and differences between treatments were not significant (Figure 5.2). During spring 2005, soil moisture was quite variable between dates but there were no significant differences between treatments (P > 0.05). A sharp decline in soil moisture content was observed from October 2005 onward in both treatments but soil moisture on 15th December 2005 (32.2 ± 1.95 % vs 22.8 ± 0.53 %) and 14th February 2006 (31.0 ± 0.2 % vs 20.6 ± 0.54 %) was significantly higher in OP than TP, respectively. A similar trend was observed on 26th April 2006 and 31st May 2006. The repeated measures analyses revealed that soil moisture content at 0-150 mm depth remained significantly higher in OP than TP (P < 0.0001) over the period of the trial (Table 5.1).

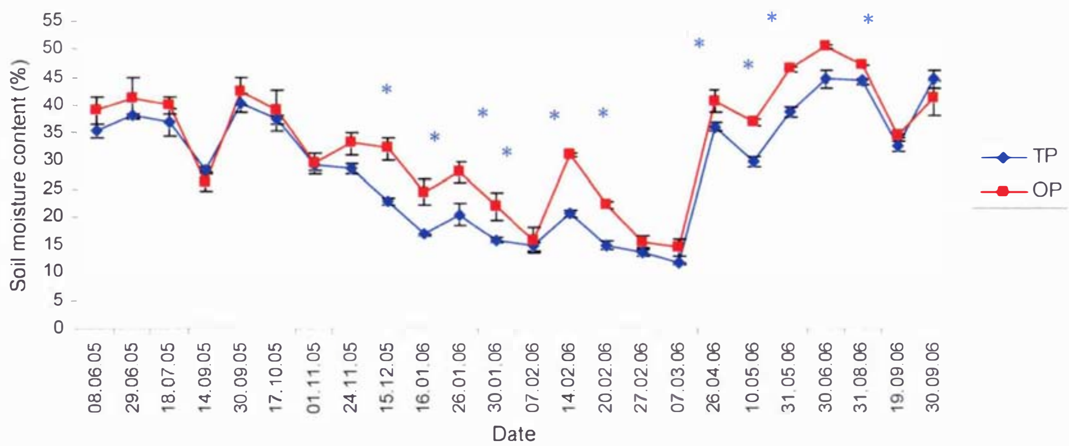


Figure 5.2 Volumetric soil moisture content (%) at 0-150 mm depth in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment * denotes significance at P < 0.05.

### 5.3.3.3 0-300 mm depth

The date-wise mean soil moisture trend is given in Figure 5.3. Date-wise analysis revealed that soil moisture contents on 20th February 2006 were significantly higher (P = 0.0344) in OP than TP (21.9 ± 1.05 % vs 14.7 ± 1.25 %, respectively). Significant differences were again measured on 10th May 2006 (36.8 ± 0.65 % vs 31.9 ± 0.60 %) and 30th June 2006 (39.9 ± 0.30 % vs 35.4 ±

1.02 %) when soil moisture contents were significantly higher (P = 0.0076, P = 0.0452) in OP than TP. The repeated measures analyses also confirmed that soil moisture contents in the 0-300 mm soil depth were significantly higher (P = 0.0004) in OP than TP over the study period (Table 5.1).

Table 5.1 Least square means for volumetric soil moisture content (%) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Treatment | Soil moisture (%) at different depths (mm) | | | | |
|---|---|---|---|---|---|
| | 0-150 | 0-300 | 150-300 | 0-450 | 350-450 |
| OP | 32.90 | 29.17 | 25.42 | 30.05 | 31.81 |
| TP | 29.10 | 27.38 | 25.61 | 25.95 | 23.13 |
| SE | | | | | |
| OP | 0.32 | 0.39 | 0.83 | 0.39 | 1.45 |
| TP | 0.23 | 0.28 | 0.59 | 0.27 | 1.02 |
| Significance | <0.0001 | 0.0004 | 0.8492 | <0.0001 | <0.0001 |

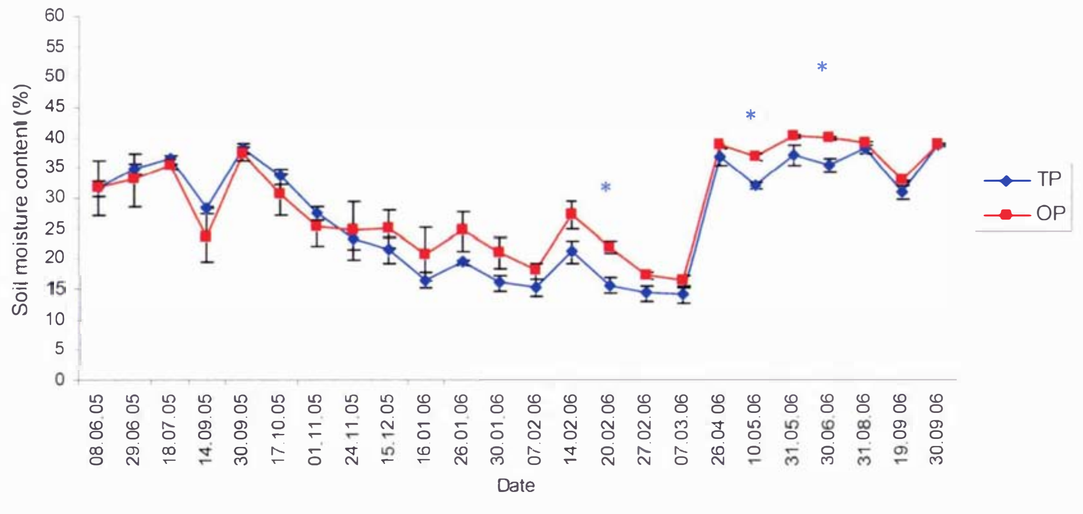


Figure 5.3 Volumetric soil moisture content (%) at 0-300 mm depth in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

The results from date-wise analyses of soil moisture contents in the 150-300 mm depth were similar between treatments except on 30th September 2005

(Appendix 5.1) The repeated measures analyses revealed that there were no significant differences (P = 0.8492) in soil moisture contents between treatments over the period of the trial (Table 5.1).

### 5.3.3.5 0-450 mm depth

Summer and autumn moisture deficit was greater in TP than OP in 2005-06 (Figure 5.4). For example, soil moisture content was significantly higher (P = 0.0351) in OP than TP on 24th November, (27.7 ± 1.8 % vs 21.4 ± 1.12 %, respectively) with similar trend on 15th December 2005, 16th January and 20th February 2006. Nevertheless, significant differences were also noted at times until late June 2006 (Figure 5.4). The over time analyses (repeated measures) confirmed that soil moisture deficit was significantly greater in TP than OP (Table 5.1).

The soil moisture contents at 300-450 mm depth were significantly higher (P = 0.0389) in OP than TP on 10th May 2006 (Appendix 5.2). The repeated measures analyses showed significant (P < 0.0001) differences between treatments with OP having higher soil moisture than TP over the period of trial (Table 5.1).

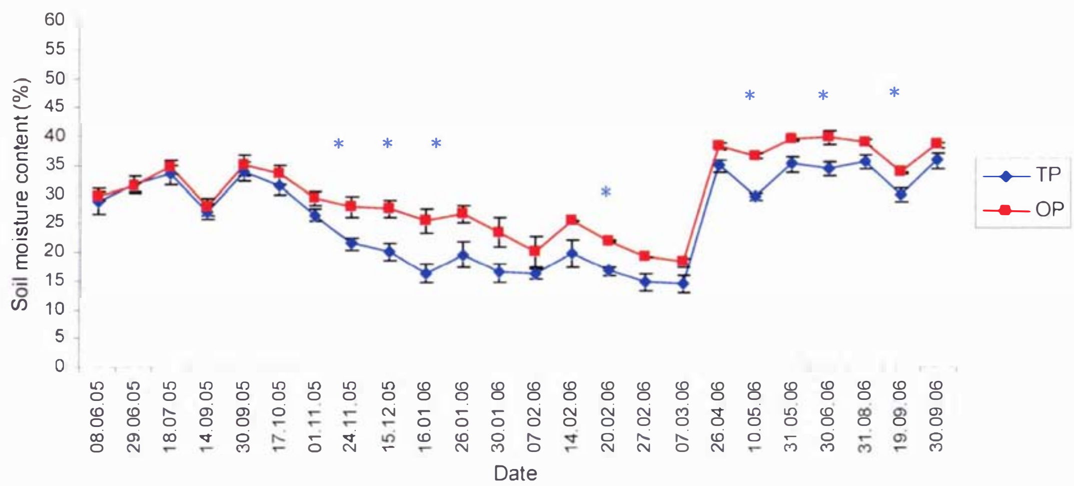


Figure 5.4 Volumetric soil moisture content (%) at 0-450 mm depth in open pasture (OP) and tree pasture (TP) treatments at Moginie, manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

### 5.3.4 Surface runoff

The difference in cumulative runoff between OP and TP over the study period was non-significant at 5 % (406.2 ± 52.94 mm vs 217 ± 36 mm, respectively) due to marked variability between plots within treatments (CV = 34). However, values were significant at 10 % (P = 0.0832). The cumulative runoff totals for OP and TP were 24 % and 13 % of cumulative rainfall (including simulated rainfall in April 2006) for the study period, respectively. Differences in cumulative runoff for the seasons between treatments were only significant in spring 2006 (Table 5.2) when analysed at 10 % (P = 0.0701). The bulk of runoff occurred in winter 2006 from both OP and TP (41.6 % each) of their respective total runoff followed by spring 2006 (26.7 % vs 22.2 %, respectively).

The reduction in cumulative runoff volume in spring 2006 compared with winter 2006 was more severe from TP than OP (47 % vs 36 %, respectively). Also, in spring 2006, the difference in mean runoff volume between OP and TP (108.64 ± 3.5 mm vs 48.32 ± 16.3 mm; P = 0.0701, respectively) was greater than spring 2005 (55.94 ± 7.9 mm 32.24 ± 11.2 mm; P = 0.2432, respectively). This indicated that trees were more effective in spring 2006 in reducing runoff than spring 2005. The repeated measures analyses revealed that runoff was significantly greater from OP than TP (P < 0.0001) during the period of study.

Event-wise runoff (mm) is shown in Figure 5.5. Despite a clear trend for runoff being higher from OP than TP, results were not significant in spring 2005. In 2005, the major runoff event occurred on 5$^{th}$ October and yielded mean totals of 37.2 ± 2.64 mm and 22.1 ± 7.49 mm (P = 0.2552) of runoff from OP and TP, respectively. Variability also occurred during the simulated rainfall events on 1$^{st}$ and 16$^{th}$ April 2006 and differences in runoff remained non-significant between treatments (Figure 5.5). However, differences between treatments were significant in the relatively small runoff events on 18$^{th}$ and 25$^{th}$ April 2006 when OP had greater runoff (P = 0.0017, P = 0.0007) than TP (1.2 ± 0.005 mm vs 0.2 ± 0.09 mm and 0.83 ± 0.035 mm vs 0.05 ± 0.052 mm, respectively). Such differences were again observed on the 4$^{th}$ and 12$^{th}$ June 2006 when runoff was significantly higher (P = 0.0343, P = 0.0471) from OP than TP (16.5 ±1.29 mm vs 6.8 ± 1.97 mm and 14.1 ± 0.34 mm vs 5.3 ± 2.07 mm, respectively).

During July and August 2006, runoff was statistically similar between treatments. However, on 4th October 2006, runoff was again significantly higher (P = 0.0331) from OP than TP (12.6 ± 0.36 mm vs 3.1 ± 1.99 mm, respectively). Similarly, the runoff events on 8th and 15th November 2006 were also significantly different between treatments (P = 0.0051, P = 0.0415) when OP had higher runoff than TP (9.5 ± 0.85 mm vs 1.6 ± 0.97 mm and 16.5 ± 1.84 mm vs 5.8 ± 2.28 mm, respectively). The maximum runoff in a single event in 2006 occurred on 22nd October when OP and TP yielded 51.9 ± 0.8 mm and 27.3 ± 8.4 mm runoff (P = 0.123), respectively.

Table 5.2 Seasonal runoff (mm) comparison between open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Tmt | Spring-05 | Summer-06 | Autumn-06 | Winter-06 | Spring-06 | Total |
|---|---|---|---|---|---|---|
| OP | 55.94 | NA | 72.72 | 169.11 | 108.64 | 406 |
| TP | 32.24 | NA | 46.28 | 90.55 | 48.32 | 217 |
| SEM | | | | | | |
| OP | 7.9 | NA | 19.3 | 28.4 | 3.5 | 52.9 |
| TP | 11.2 | NA | 5.3 | 22.4 | 16.3 | 36.0 |
| Sig. | 0.243 | NA | 0.137 | 0.106 | 0.070 | 0.083 |

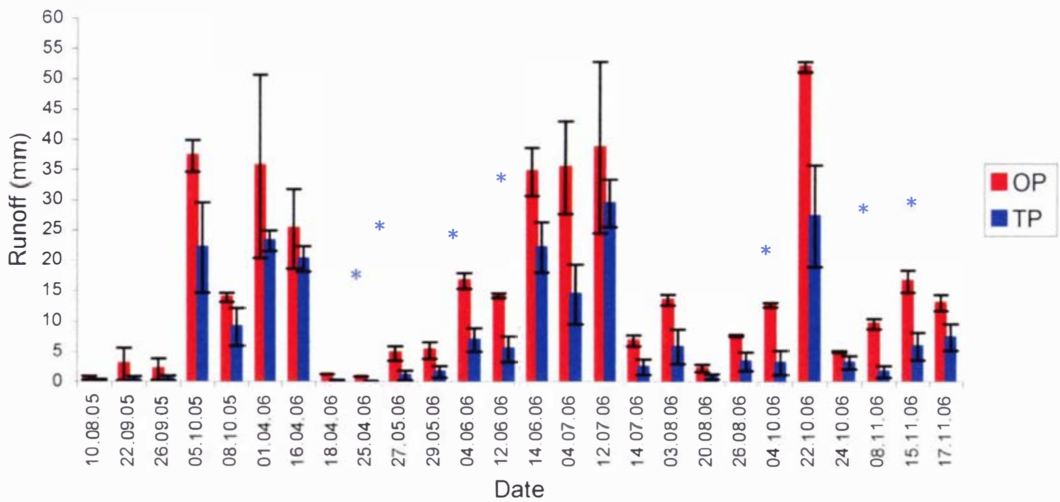


Figure 5.5 Event-wise surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

### 5.3.5 Sediment load in surface runoff

The differences in event wise TSS concentrations between treatments were only significant (P = 0.0252) on 4th June 2006 when OP had a greater value (Figure 5.6) than TP (368 ± 60.38 mg $L^{-1}$ vs 208 ± 18.17 mg $L^{-1}$, respectively). Similar to TSS, differences between treatments for ISS (241 ± 49.5 mg $L^{-1}$ vs 136 ± 12.3 mg $L^{-1}$; P = 0.0417) and OSS concentrations (127 ± 10.79 mg $L^{-1}$ vs 72 ± 6.62 mg $L^{-1}$; P = 0.0100) were only significant on 4th June 2006 (Figures 5.7, 5.8). The runoff event on 4th June 2006 occurred soon after sheep grazing and the suspended solid concentrations were the highest of all events during the study period. Concentrations were also affected by the soil cover (either pasture or trees with leaves) or season. For example, the concentrations were low in the runoff event on 22nd October 2006 from OP and TP, despite the sizeable nature of this event (TSS = 9.5 ± 1.34 mg $L^{-1}$ vs 12.6 ± 1.62 mg $L^{-1}$; P = 0.2933, respectively) due to substantial ground cover as plots were not grazed after 4th June 2006. The repeated measures analyses determined that differences between treatments for concentrations of TSS, ISS and OSS were not significant over time (Table 5.4).

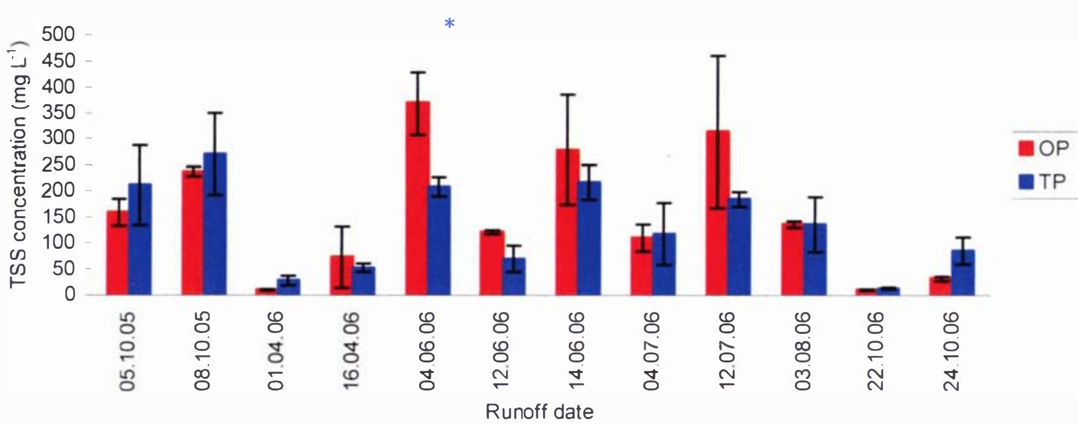


Figure 5.6 Total suspended solids (TSS) concentration (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

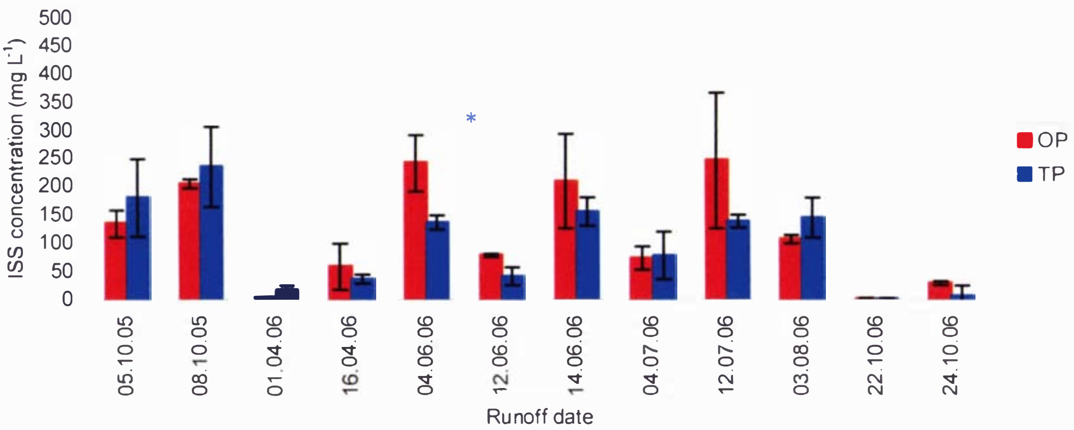


Figure 5.7 Inorganic suspended solids (ISS) concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

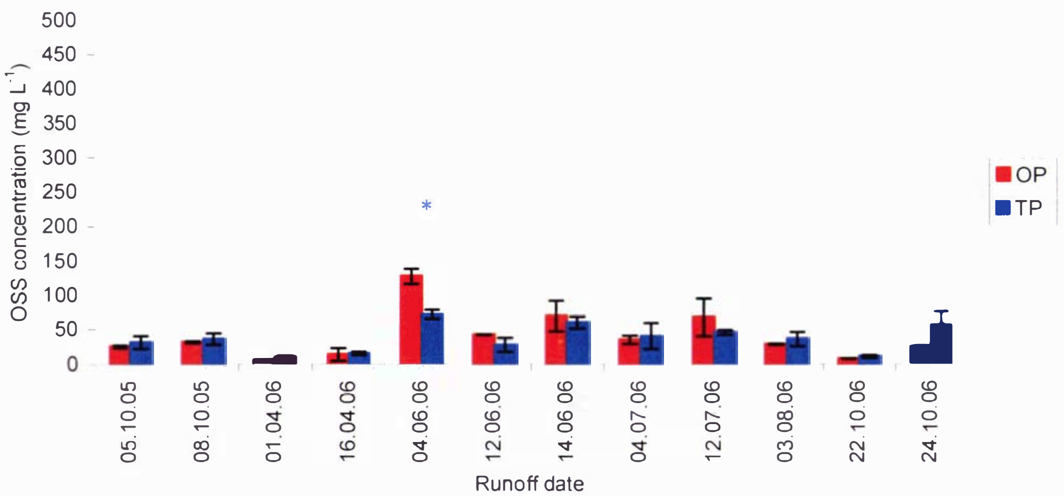


Figure 5.8 Organic suspended solids (OSS) concentrations (mg $L^{-1}$) in surface runoff in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

The cumulative TSS loss, over the study period, was significantly greater ($P = 0.0158$) from OP than TP (443 ± 67.2 kg $ha^{-1}$ vs 212 ± 27.9 kg $ha^{-1}$, respectively) (Table 5.3). The fractionation of suspended solids into inorganic (ISS) and organic suspended solids (OSS) revealed that the bulk of suspended load was in the form of ISS (Table 5.3). The cumulative ISS losses were 329 ± 59.8 kg $ha^{-1}$ vs 155 ± 18.6 kg $ha^{-1}$ from OP and TP, respectively ($P = 0.0152$). The OSS losses were 114 ± 7.3 vs 57 ± 9.7 from OP and TP respectively (P =

0.0204). Therefore, ISS and OSS constituted about 74 % vs 73 % and 26 % vs 27 % of total solids losses from OP and TP treatment, respectively.

The seasonal analysis revealed that TSS losses were the highest in winter 2006 for both OP (73 %) and TP (63.6 %) (Table 5.3). Spring 2005 losses were 21 % and 26 % while spring 2006 losses were the least (1.6 % vs 2.8 %) from OP and TP, respectively. Although the autumn contribution was 4 % and 7.5 % for OP and TP the major share was from simulated rainfall events. Spring 2006 was the only season when OSS losses surpassed ISS in both OP and TP (Table 5.3).

Table 5.3 Seasonal suspended solid losses (kg ha$^{-1}$) in surface runoff (mm) from open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Season | Solids | Treatment | | SE | | Sig. |
|---|---|---|---|---|---|---|
| | | OP | TP | OP | TP | |
| Spring-05 | TSS | 93 | 55 | 16.94 | 11.94 | 0.1393 |
| | ISS | 79 | 46 | 14.97 | 10.23 | 0.1407 |
| | OSS | 14 | 9 | 1.96 | 1.88 | 0.1577 |
| Autumn-06 | TSS | 18 | 16 | 9.14 | 2.07 | 0.8091 |
| | ISS | 13 | 11 | 8.58 | 1.97 | 0.7477 |
| | OSS | 5 | 5 | 0.56 | 0.49 | 0.6322 |
| Winter-06 | TSS | 325 | 135 | 41.68 | 25.04 | 0.0139 |
| | ISS | 236 | 97 | 36.55 | 17.8 | 0.0161 |
| | OSS | 89 | 38 | 5.13 | 7.31 | 0.0111 |
| Spring-06 | TSS | 7 | 6 | 0.59 | 1.94 | 0.7991 |
| | ISS | 1 | 1 | 0.24 | 0.76 | 0.7797 |
| | OSS | 6 | 5 | 0.35 | 1.26 | 0.5812 |
| Total | TSS | 443 | 212 | 67.2 | 27.9 | 0.0158 |
| | ISS | 329 | 155 | 59.8 | 18.6 | 0.0152 |
| | OSS | 114 | 57 | 7.3 | 9.7 | 0.0204 |

Event-wise analysis of TSS (Figure 5.9), ISS (Figure 5.10) and OSS (Figure 5.11) losses showed that marked variability occurred between plots within treatments and despite a clear pattern for less suspended solids in TP, differences between treatments were not significant for all the events. For example, on 5$^{th}$ October 2005, the mean values for OP and TP were not

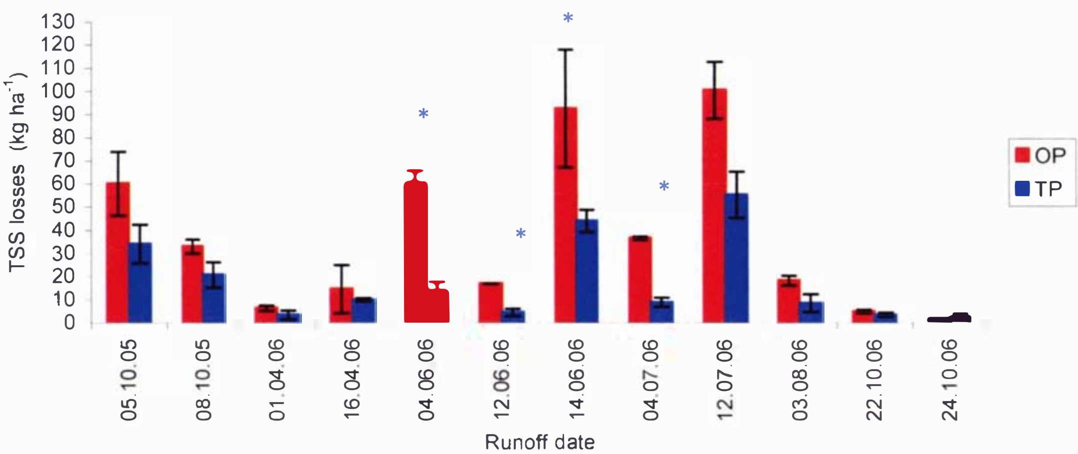


Figure 5.9 Total suspended solids (TSS) losses (kg ha$^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

significantly different (TSS = 60 ± 13.8 kg ha$^{-1}$ vs 34 ± 8.3 kg ha$^{-1}$) due to marked variability (CV = 40). However, winter loads were significantly different between treatments except on 12$^{th}$ July 2006. For example, on 4$^{th}$ June 2006, the TSS were about 4 fold higher (P = 0.0017) from OP than TP (60.32 ± 5.24 kg ha$^{-1}$ vs 14 ± 3.5 kg ha$^{-1}$, respectively). Similarly, on 4$^{th}$ of July 2006, the TSS losses were also four fold higher from OP than TP (36.6 ± 0.8 kg ha$^{-1}$ vs 9 ± 2 kg ha$^{-1}$, respectively) (P = 0.0009). The repeated measures analyses confirmed that TSS, ISS and OSS losses were significantly greater from OP than TP over the experimental period (Table 5.4).

Table 5.4 Least square means for suspended solids concentrations (mg L$^{-1}$) and losses (kg ha$^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Treatment | TSS | | ISS | | OSS | |
|---|---|---|---|---|---|---|
| | conc | losses | conc | losses | conc | losses |
| OP | 154.0 | 36.8 | 114.0 | 27.4 | 40.0 | 9.4 |
| TP | 136.7 | 17.6 | 99.5 | 13.0 | 37.2 | 4.6 |
| SE | | | | | | |
| OP | 17.66 | 2.16 | 13.85 | 1.76 | 5.50 | 0.47 |
| TP | 12.66 | 1.55 | 9.93 | 1.29 | 3.94 | 0.34 |
| Sig. | 0.4289 | <0.0001 | 0.4051 | <0.0001 | 0.6586 | <0.0001 |

The highest losses of suspended solids in a single runoff event were recorded on 12th July 2006 when OP and TP yielded a mean total of 100.5 ± 0.06 kg ha$^{-1}$ and 55.5 ± 1.6 kg ha$^{-1}$ solids, respectively and these losses were significantly different (P = 0.006).

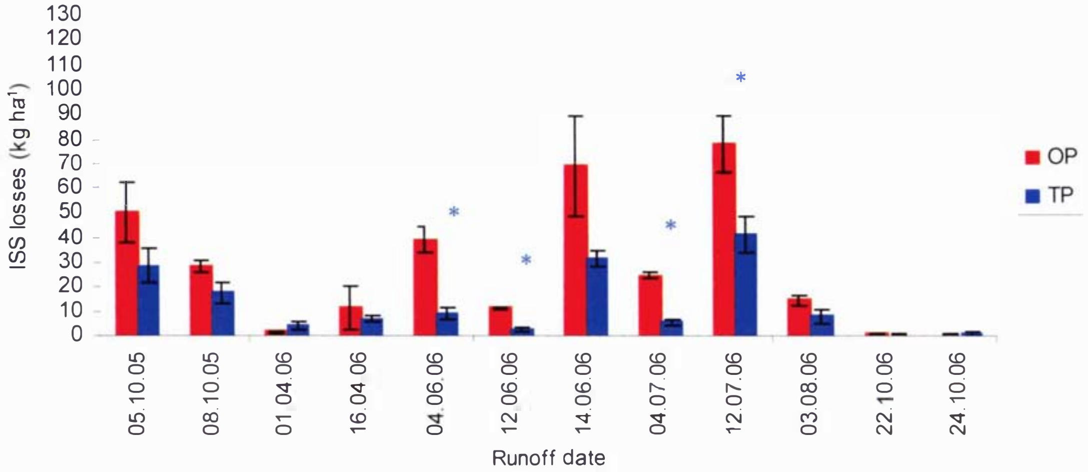


Figure 5.10 Inorganic suspended solids (ISS) losses (kg ha$^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

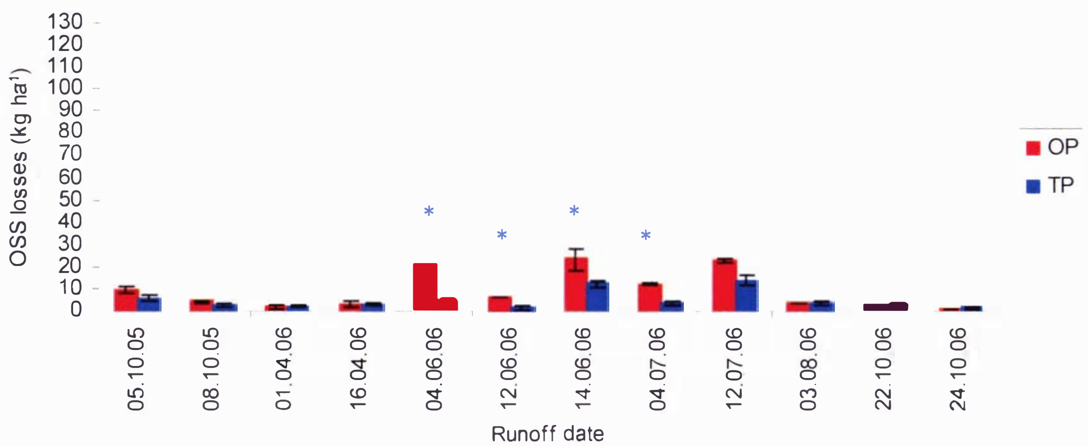


Figure 5.11 Organic suspended solids (ISS) losses (kg ha$^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

### 5.3.6 Phosphorus losses in runoff water

Total P concentrations were not significantly different ($P > 0.05$) between treatments for any of the runoff events during the study period (Table 5.5). However, concentrations were greatly affected by P fertiliser application. For example, concentrations increased substantially on 1st April 2006 (5.08 ± 0.91 mg $L^{-1}$ and 3.77 ± 1.19 mg $L^{-1}$ for OP and TP, respectively) due to application of Single Super Phosphate (P = 45 kg $ha^{-1}$) compared with the previous runoff event on 8th October 2005 ( 0.87 ± 0.33 mg $L^{-1}$ and 0.78 ± 0.09 mg $L^{-1}$ for OP and TP, respectively). Similarly, concentrations peaked (282.63 ± 6.37 mg $L^{-1}$ and 287.76 ± 16.95 mg $L^{-1}$ for OP and TP, respectively) after application of fertiliser (P= 50 kg $ha^{-1}$) compared with the previous event without application of fertiliser on 22nd October 2006 (0.65 ± 0.02 mg $L^{-1}$ and 0.79 ± 0.16 mg $L^{-1}$ for OP and TP, respectively).

Table 5.5 Total P concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Date | Treatment | | LSD | Significance |
|---|---|---|---|---|
| | OP | TP | | |
| 05.10.05 | 1.02 | 0.84 | 0.34 | 0.2140 |
| 08.10.05 | 0.87 | 0.78 | 0.69 | 0.7283 |
| 01.04.06 | 5.08 | 3.77 | 5.20 | 0.5229 |
| 16.04.06 | 0.98 | 0.75 | 0.53 | 0.2911 |
| 18.04.06 | 1.56 | 1.02 | 1.03 | 0.1948 |
| 29.05.06 | 2.05 | 1.42 | 1.72 | 0.3637 |
| 04.06.06 | 51.11 | 56.91 | 30.73 | 0.6281 |
| 12.06.06 | 4.39 | 4.88 | 2.62 | 0.6287 |
| 14.06.06 | 2.52 | 3.46 | 2.45 | 0.3441 |
| 04.07.06 | 1.34 | 1.9 | 1.74 | 0.4126 |
| 12.07.06 | 1.11 | 1.41 | 0.80 | 0.336 |
| 21.08.06 | 0.89 | 1.96 | 4.77 | 0.5261 |
| 26.08.06 | 0.69 | 0.89 | 0.92 | 0.5712 |
| 04.10.06 | 0.65 | 1.67 | 3.24 | 0.3906 |
| 22.10.06 | 0.65 | 0.79 | 0.65 | 0.5718 |
| 24.10.06 | 282.63 | 287.76 | 71.44 | 0.8517 |
| 08.11.06 | 3.5 | 13.35 | 26.07 | 0.3541 |
| 15.11.06 | 3.27 | 3.71 | 5.36 | 0.8337 |
| 17.11.06 | 2.31 | 2.09 | 0.63 | 0.3871 |

Sheep grazing also affected the total P concentrations. For example, the concentrations in a runoff event following sheep grazing increased significantly on 4th June 2006 (51.11 ± 1.6 mg $L^{-1}$ and 56.91 ± 7.35 mg $L^{-1}$ for OP and TP, respectively) compared with the previous event on 29th May 2006 (2.05 ± 0.04 mg $L^{-1}$ and 1.42 ± 0.41 mg $L^{-1}$ for OP and TP, respectively). Concentrations in the subsequent runoff events dropped sharply but remained well above the levels (0.03 P mg $L^{-1}$) required to prevent aquatic weed growth in fresh water bodies (Australia and New Zealand Environment and Conservation Council, 2000).

Cumulative losses of total P were not significantly ($P > 0.05$) different between treatments for the study period (Table 5.6). The total losses from OP were 29 ± 1.0 kg $ha^{-1}$ while losses from TP were 17 ± 5.1 kg $ha^{-1}$. Seasonal comparison between treatments revealed that spring 2006 contributed the largest P losses of all seasons from both treatments. The spring 2006 losses from OP and TP were 54 % and 59 %, respectively, but values were not significantly different between treatments (Table 5.6). Winter losses were 37 % and 33 % of the cumulative P loads from OP and TP, respectively. The major contribution to the spring 2006 losses was from the post P fertiliser application event on 24th October, while winter losses were greatly accelerated by the post grazing event on 4th June 2006. The autumn contribution was 7 % and 6 % from OP and TP, respectively. However, major autumn losses were from the simulated rainfall event on 1st April 2006. Spring 2005 losses accounted for about 2 % in both treatments (Table 5.6).

Table 5.6 Seasonal comparison for total P and DRP losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Tmt | Spring-05 | | Autumn-06 | | Winter-06 | | Spring-06 | | Total | |
|---|---|---|---|---|---|---|---|---|---|---|
| | total P | DRP | total P | DRP | total P | DRP | total P | DRP | Total P | DRP |
| OP | 0.50 | 0.30 | 1.99 | 1.17 | 10.93 | 1.96 | 15.59 | 2.79 | 29 | 6.2 |
| TP | 0.25 | 0.15 | 1.07 | 0.59 | 5.58 | 1.21 | 10.02 | 1.00 | 17 | 2.9 |
| SE | | | | | | | | | | |
| OP | 0.12 | 0.10 | 0.44 | 0.18 | 0.85 | 0.49 | 0.14 | 0.32 | 1.0 | 0.25 |
| TP | 0.08 | 0.05 | 0.32 | 0.16 | 1.41 | 0.26 | 3.64 | 0.39 | 5.1 | 0.74 |
| Sig. | 0.1460 | 0.1830 | 0.1686 | 0.0961 | 0.0703 | 0.2069 | 0.3670 | 0.0469 | 0.1957 | 0.0433 |

Event-wise total P losses (kg $ha^{-1}$) were not significantly different (P > 0.05) between treatments for each runoff event. However, loads were significantly different on 18th April 2006 when OP had higher losses compared with TP (0.02 ± 0.003 kg $ha^{-1}$ vs 0.003 ± 0.0014 kg $ha^{-1}$), respectively. Such differences were not detected throughout the winter. However, in spring 2006, differences were found on 4th October and 8th November when OP again had higher losses than TP (0.08 ± 0.0003 kg $ha^{-1}$ vs 0.03 ± 0.009 kg $ha^{-1}$ and 0.33 ± 0.048 kg $ha^{-1}$ vs 0.11 ± 0.039 kg $ha^{-1}$), respectively. All other differences between treatments for events in spring 2006 (Figure 5.12) remained non-significant (P > 0.05). However, repeated measures analysis revealed that losses were significantly higher (P = 0.0362) from OP than TP over the study period (Table 5.7).

Table 5.7 Least square means of total P and DRP concentrations (mg $L^{-1}$) and losses (kg $ha^{-1}$) in surface runoff (mm) ) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Treatment | total P | | DRP | |
|---|---|---|---|---|
| | Conc. | losses | Conc. | losses |
| OP | 19.26 | 1.53 | 2.92 | 0.33 |
| TP | 20.52 | 0.89 | 2.25 | 0.15 |
| SE | | | | |
| OP | 1.30 | 0.24 | 0.42 | 0.03 |
| TP | 0.94 | 0.17 | 0.30 | 0.02 |
| Sig. | 0.4352 | 0.0362 | 0.2061 | <0.0001 |

Like the concentrations, total loads were also affected by grazing and P fertilisation. For example, the losses on 1st April 2006 sufficiently increased as a result of P fertiliser application (1.67 ± 0.45 kg $ha^{-1}$ vs 0.87 ± 0.28 kg $ha^{-1}$) compared with the previous event on 8th October 2005 (0.12 ± 0.05 kg $ha^{-1}$ vs 0.08 ± 0.03 kg $ha^{-1}$) from OP and TP, respectively. Similarly, losses were the highest of all events due to P fertilisation on 24th October 2006 (13.93 ± 0.13 kg $ha^{-1}$ vs 9.33 ± 2.4 kg $ha^{-1}$) from OP and TP, respectively. The losses from these two events alone accounted for 54 % and 60 % of the total P losses from OP and TP, respectively.

Total P losses were also affected by grazing. For example, loads on 4th June 2006 increased greatly due to grazing (8.45 ± 0.39 kg ha$^{-1}$ vs 3.93 ± 1.10 kg ha$^{-1}$) compared with the previous event on 29th May 2006 (0.07 ± 0.02 kg ha$^{-1}$ vs 0.04 ± 0.032 kg ha$^{-1}$) from OP and TP, respectively. Conversely, despite grazing, the losses on 8th November, 2006 were quite low (0.33 ± 0.04 kg ha$^{-1}$ vs 0.1 ± 0.03 kg ha$^{-1}$) compared with the event on 4th June 2006. Surface runoff on 4th June 2006 was more (16.6 ± 1.29 mm vs 6.8 ± 1.97 mm) than on 8th November, 2006 (9.5 ± 0.85 mm vs 1.6 ± 0.97 mm) from OP and TP, respectively.

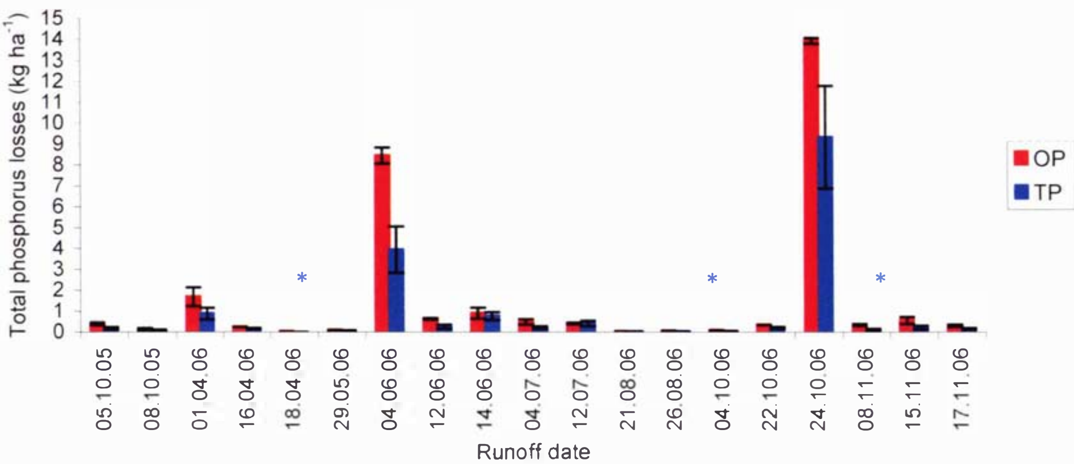


Figure 5.12 Total phosphorus losses (kg ha$^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

The differences in DRP concentrations between treatments were only significant ($P = 0.0052$) on 18th April 2006 when OP had higher values than TP (1.14 ± 0.06 mg L$^{-1}$ vs 0.4 ± 0.11 mg L$^{-1}$, respectively). Like total P, DRP concentrations were also affected by grazing and P fertilisation. The fertiliser application (P = 45 kg ha$^{-1}$) on 1st April 2006 raised the concentrations (Figure 5.13) markedly (2.87 ± 0.67 mg L$^{-1}$ and 2.06 ± 0.56 mg L$^{-1}$ for OP and TP, respectively) compared with the previous event on 8th October 2005 (0.18 ± 0.09 mg L$^{-1}$ and 0.41 ± 0.05 mg L$^{-1}$ for OP and TP, respectively). Similarly, the application of P fertiliser (P = 50 kg ha$^{-1}$) on 24th October 2006, raised the DRP concentrations to the highest of all events (31 ± 2.8 mg L$^{-1}$ and 18.3 ± 6.3 mg L$^{-1}$ for OP and TP, respectively). The higher concentrations in the latter event were due to the application of more fertiliser per ha and less runoff. Also, the soil being at field capacity contributed to quick P dilution and its transfer to runoff water rather than drainage while during the simulated rainfall event on 1st April 2006, substantial water was required to saturate the soil and P losses were probably more in drainage water than runoff.

The grazing impact on DRP concentrations was also pronounced in both treatments. The concentrations on 4th June 2006 increased greatly due to grazing (3.9 ± 0.7 mg $L^{-1}$ and 4.8 ± 0.7 mg $L^{-1}$ for OP and TP, respectively) compared with the previous event on 29th May 2006 (1.02 ± 0.07 mg $L^{-1}$ and 0.49 ± 0.2 mg $L^{-1}$ for OP and TP, respectively). Similarly, concentrations on 8th November 2006 were also reasonably high (2.55 ± 0.35 mg $L^{-1}$ vs 2.37 ± 0.61 mg $L^{-1}$) and remained almost at the same level in subsequent events on 15th and 17th November 2006 (Figure 5.13) from OP and TP, respectively.

There was a strong linear relationship between total P concentrations and DRP in both treatments. However, the relationship in OP was stronger (Figure 5.14) than TP (Figure 5.15).

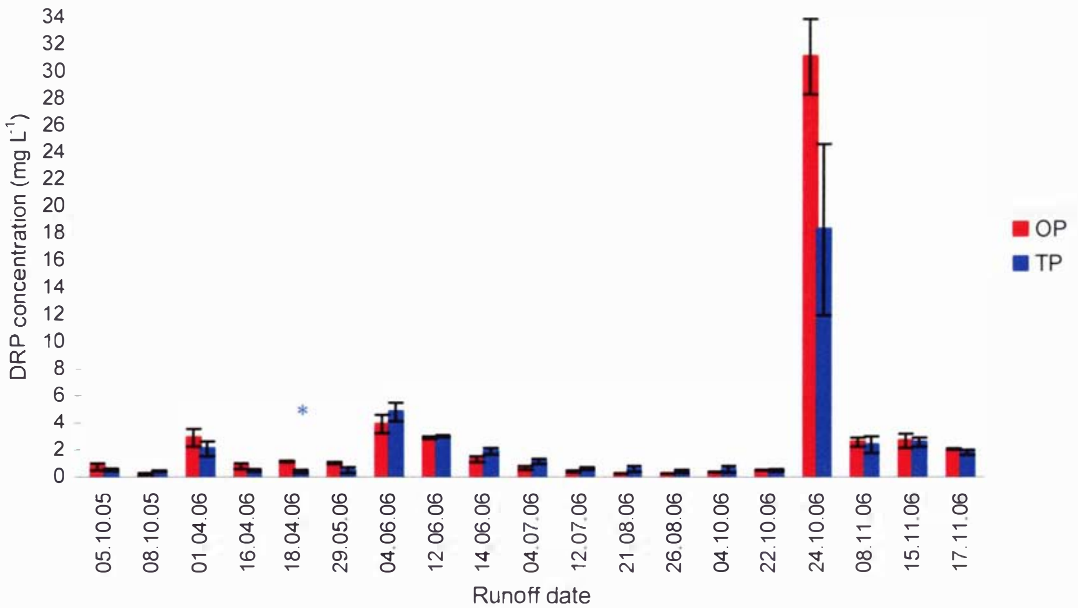


Figure 5.13 DRP concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

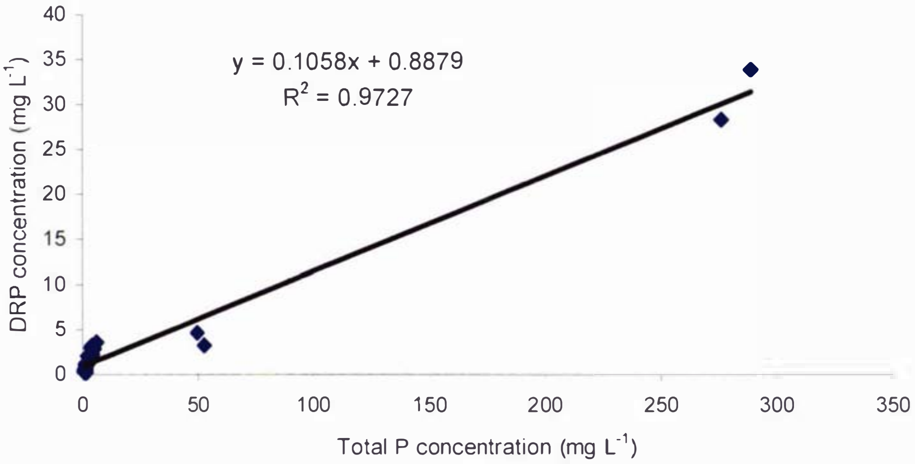


Figure 5.14 Relationship between total P and DRP concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) treatment at Moginie, Manawatu. (n = 38).

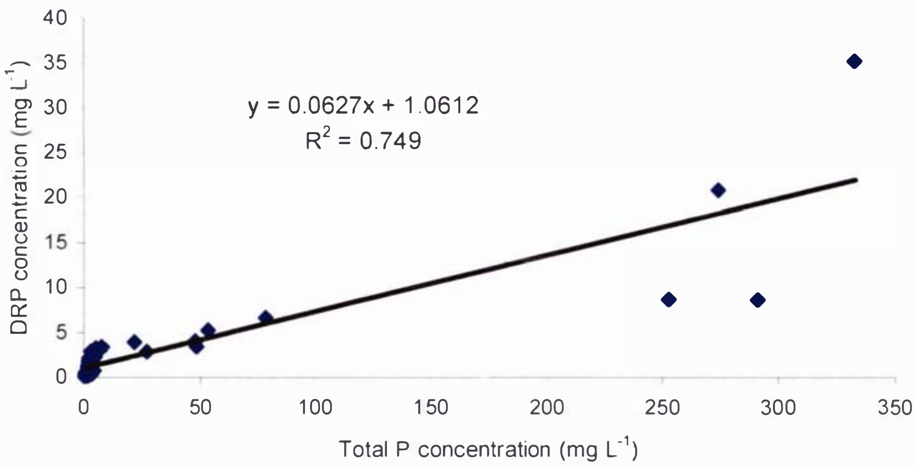


Figure 5.15 Relationship between total P and DRP concentrations (mg $L^{-1}$) in surface runoff (mm) in tree pasture (TP) treatment at Moginie, Manawatu. (n = 76).

The total cumulative DRP losses (Table 5.6) were significantly greater from OP than TP (6.22 ± 0.25 kg $ha^{-1}$ vs 2.95 ± 0.74 kg $ha^{-1}$) and accounted for 21 % and 17 % of total P losses, respectively ($P < 0.05$). Seasonal comparison showed that DRP losses were generally in line with the total P losses (Table 5.6). For example, as expected, major losses occurred in winter and spring 2006 from both treatments. Spring 2006 losses were significantly higher from OP (45 %) than TP (34 %) ($P = 0.0469$). This was expected because of significantly lower runoff from TP than OP for some events in November 2006 (Figure 5.5). Winter contribution was 31 % and 41 % of corresponding cumulative DRP values from

OP and TP respectively, but losses were not significantly different between treatments.

Many of the event-wise DRP losses in runoff were significantly different between treatments (Figure 5.16). Autumn events on 18$^{th}$ April and 29$^{th}$ May 2006 were significantly different (Figure 5.16) between treatments (P = < 0.0001, 0.0146). In winter 2006, the losses were similar between treatments except on 12$^{th}$ June 2006 when OP had higher losses (P = 0.0442) than TP (0.41 ± 0.02 kg ha$^{-1}$ vs 0.15 ± 0.05 kg ha$^{-1}$). However, in spring 2006, losses were significantly higher from OP than TP for all the runoff events except on 24$^{th}$ October 2006 (Figure 5.16).

The P fertilisation and grazing impact was substantial in both treatments. For example, P fertilisation on 1$^{st}$ April 2006 increased the DRP losses substantially (0.92 ± 0.19 kg ha$^{-1}$ and 0.48 ± 0.13 kg ha$^{-1}$ for OP and TP, respectively). Similarly the post fertilisation losses on 24$^{th}$ October 2006 from OP and TP were the highest of all events (1.53 ± 0.08 kg ha$^{-1}$ and 0.58 ± 0.32 kg ha$^{-1}$, respectively).

Sheep grazing also enhanced the DRP losses in both treatments. For example, losses on 4$^{th}$ June 2006 increased as a result of grazing (0.65 ± 0.16 kg ha$^{-1}$ and 0.32 ± 0.08 kg ha$^{-1}$ for OP and TP, respectively) compared with the previous event on 29$^{th}$ May 2006 (0.05 ± 0.009 kg ha$^{-1}$ and 0.009 ± 0.005 kg ha$^{-1}$ for OP and TP). Similarly, losses on 8$^{th}$ November 2006 were also as a result of grazing and remained substantial in the subsequent events on 15$^{th}$ and 17$^{th}$ November 2006 in both treatments (Figure 5.16).

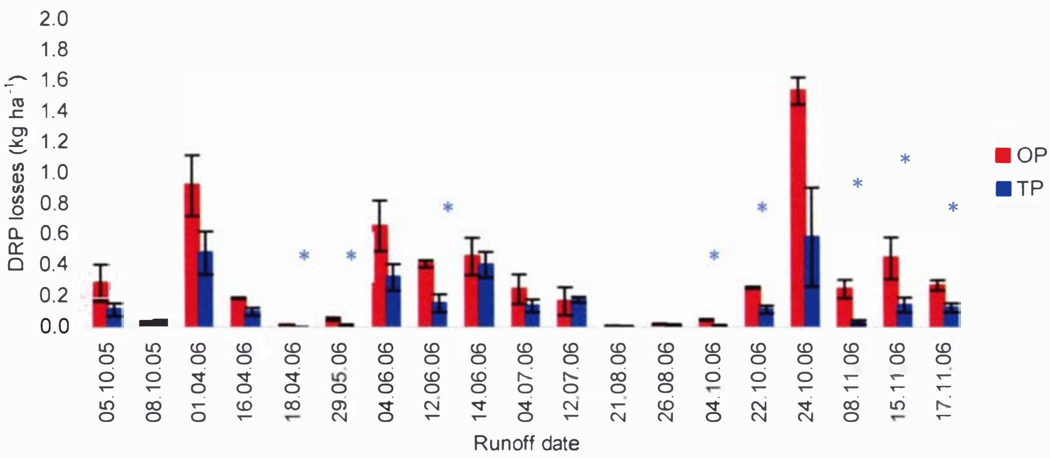


Figure 5.16 DRP losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

### 5.3.7 Nitrogen losses in runoff water

The TN concentrations were similar to TKN for most of the events due to non-traceable $NO_3^-$-N concentrations (Figure 5.17). Generally, TN increased in post grazing and fertiliser events. For example, TN concentrations increased greatly from OP and TP on 4th June 2006 as a result of grazing (15.88 ± 0.63 mg $L^{-1}$ vs 18.04 ± 2.0 mg $L^{-1}$, respectively) compared with the previous event on 29th May 2006 (2.29 ± 0.21 mg $L^{-1}$ vs 5.96 ± 2.26 mg $L^{-1}$, respectively). The grazing event on 8th November had a lesser impact on TN concentration as the increase in concentration was relatively low (3.85 ± 0.27 mg $L^{-1}$ vs 7.85 ± 2.69 mg $L^{-1}$) compared with the previous event on 24th November 2006 (1.25 ± 0.01 mg $L^{-1}$ vs 2.19 ± 0.52 mg $L^{-1}$). Nevertheless, application of urea fertiliser on 17th November 2006 also increased TN concentration considerably (24.16 ± 5.41 mg $L^{-1}$ vs 9.08 ± 3.84 mg $L^{-1}$) compared with the previous event on 15th November 2006 (2.71 ± 0.2 mg $L^{-1}$ vs 5.12 ± 1.07 mg $L^{-1}$) from OP and TP, respectively. However, the impact on OP was greater than on TP (Figure 5.17).

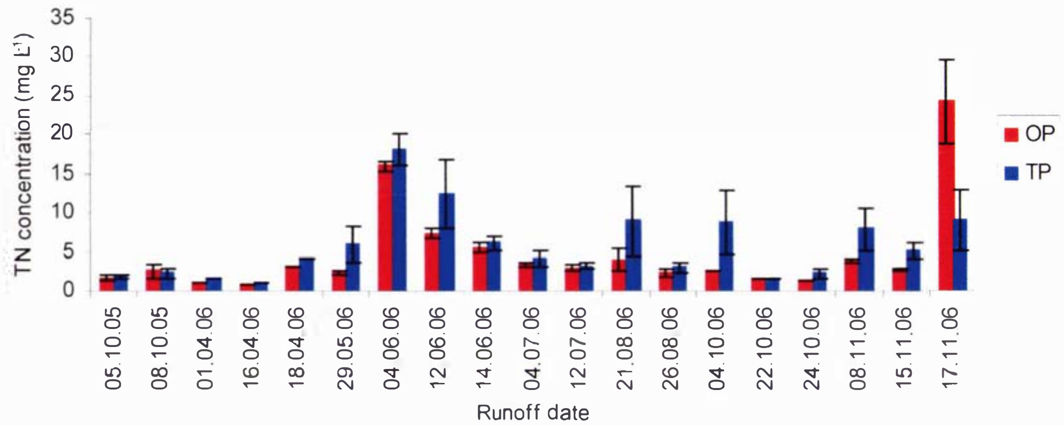


Figure 5.17 TN concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

The cumulative TN losses (table 5.8) over the study period were 15.2 ± 0.35 kg $ha^{-1}$ and 7.2 ± 1.54 kg $ha^{-1}$ from OP and TP (P = 0.0267), respectively. The major contribution was from events after grazing and urea fertiliser application. Seasonal percentile breakdown showed that winter (54 % vs 60 %) and spring 2006 (35 % vs 24 %) were the major contributors with significantly higher losses from OP than TP respectively (Table 5.8). The spring 2005 (6 % vs 9 %) and autumn 2006 (5 % vs 8 %) losses were statistically similar between treatments.

The event-wise TN losses were overall significant (Table 5.9) between treatments (repeated measures analysis) for the study period (P < 0.0001). However, TN losses were not significant for each of the events (Figure 5.18). For example, OP had higher TN losses on 29$^{th}$ May 2006 than TP (0.12 ± 0.02 kg $ha^{-1}$ vs 0.04 ± 0.01 kg $ha^{-1}$, P = 0.0171), respectively. The losses increased in the subsequent event on 4$^{th}$ June 2006 as a result of grazing and remained significant between OP and TP (2.64 ± 0.31 kg $ha^{-1}$ vs 1.13 ± 0.24 kg $ha^{-1}$, P = 0.0218), respectively. Though total losses decreased over time the grazing effect remained persistent in the subsequent events. Occasionally, losses were significantly higher from OP than TP during the study period (Figure 5.18). The losses increased as a result of urea fertiliser application (N = 40 kg $ha^{-1}$) on 17$^{th}$ November 2006 from OP and TP (3.27 ± 1.01 kg $ha^{-1}$ vs 0.76 ± 0.38 kg $ha^{-1}$, P = 0.0418), respectively.

Table 5.8 Seasonal comparison of total nitrogen (TN), ammonium-N ($NH_4^+$-N) and nitrate-N ($NO_3^-$-N) losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Season | Nutrient type | Treatment | | SE | | Sig. |
|---|---|---|---|---|---|---|
| | | OP | TP | OP | TP | |
| Spring-05 | TN | 0.96 | 0.62 | 0.02 | 0.26 | 0.4436 |
| | $NH_4^+$-N | NA | NA | NA | NA | NA |
| | $NO_3^-$-N | NA | NA | NA | NA | NA |
| Autumn-06 | TN | 0.77 | 0.58 | 0.26 | 0.06 | 0.3755 |
| | $NH_4^+$-N | NA | NA | NA | NA | NA |
| | $NO_3^-$-N | NA | NA | NA | NA | NA |
| Winter-06 | TN | 8.13 | 4.31 | 1.22 | 0.81 | 0.0563 |
| | $NH_4^+$-N | 1.58 | 0.9 | 0.41 | 0.22 | 0.1769 |
| | $NO_3^-$-N | 0.33 | 0.21 | 0.1 | 0.01 | 0.1494 |
| Spring-06 | TN | 5.33 | 1.74 | 1.1 | 0.58 | 0.0315 |
| | $NH_4^+$-N | 1.47 | 0.35 | 0.28 | 0.25 | 0.0567 |
| | $NO_3^-$-N | 0.07 | 0.06 | 0.005 | 0.02 | 0.6971 |
| Total | TN | 15.2 | 7.25 | 0.35 | 1.54 | 0.0267 |
| | $NH_4^+$-N | 3.0 | 1.25 | 0.46 | 0.13 | 0.0596 |
| | $NO_3^-$-N | 0.4 | 0.27 | 0.1 | 0.04 | 0.185 |

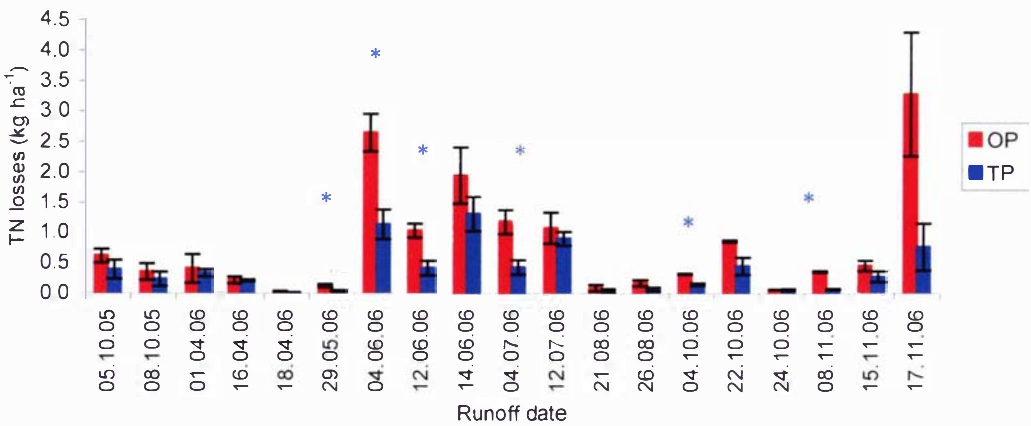


Figure 5.18 TN losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

The $NH_4^+$-N concentrations in some of the surface runoff events were too low for accurate detection (< 0.25 mg $L^{-1}$) and so the results for such events are not presented. However, the detectable concentrations were only significant between treatments (P = 0.0026) on 12th July 2006 when OP had a higher mean concentration than TP (0.28 ± 0.007 mg $L^{-1}$ vs 0.26 ± 0.002 mg $L^{-1}$), respectively (Figure 5.19). The repeated measures analyses showed (Table 5.8) that concentrations remained non-significant between treatments throughout the study period.

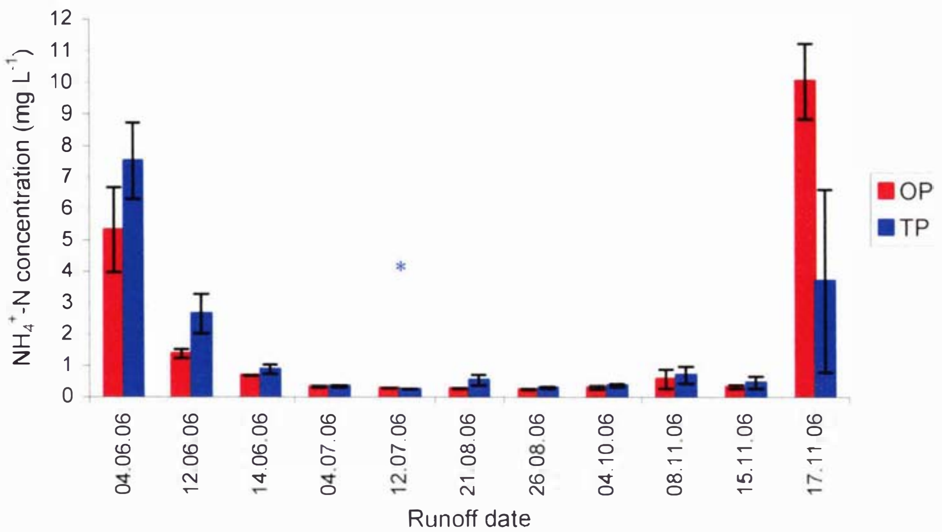


Figure 5.19 $NH_4^+$-N concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

The grazing and urea fertilisation impact was substantial in $NH_4^+$-N concentrations in runoff from both OP and TP. For example, the runoff event on 4th June 2006 that occurred soon after grazing, markedly increased the $NH_4^+$-N concentrations (5.3 ± 1.3 mg $L^{-1}$ vs 7.5 ± 1.2 mg $L^{-1}$) compared with all previous events (< 0.25, results not shown) from OP and TP, respectively. However, there was a relatively smaller impact of grazing on 8th November 2006 when the concentration did not increase greatly (0.6 ± 0.3 mg $L^{-1}$ and 0.7 ± 0.2 mg $L^{-1}$ from OP and TP respectively) compared with the previous event on 4th October 2006 (0.3 ± 0.05 mg $L^{-1}$ and 0.37 ± 0.047 mg $L^{-1}$ from OP and TP respectively). Similarly, urea fertilisation (N = 40 kg $ha^{-1}$) had a greater effect on concentration (10.05 ± 1.19 mg $L^{-1}$ and 3.7 ± 2.91 mg $L^{-1}$ from OP and TP, respectively) compared with the previous event on 15th November 2006 (0.32 ± 0.05 mg $L^{-1}$ and 0.46 ± 0.18 mg $L^{-1}$ from OP and TP, respectively) (Figure 5.19).

The cumulative $NH_4^+$-N losses (Table 5.8) were not significantly different (P = 0.0596) between OP and TP (3.0 ± 0.46 kg $ha^{-1}$ vs 1.25 ± 0.13 kg $ha^{-1}$), respectively. Thus, cumulative $NH_4^+$-N losses constituted 20 % and 17 % of TN losses from OP and TP, respectively. Seasonal losses were restricted to winter and spring 2006 only (Table 5.8). The winter and spring contribution was almost similar from OP (52 % vs 48 %) while winter losses were very high compared with spring (72 % vs 28 %), respectively.

The event-wise $NH_4^+$-N losses (Figure 5.20) were significantly greater in OP than TP (P = 0.0262) on 4th October 2006 (0.04 ± 0.007 kg $ha^{-1}$ vs 0.007 ± 0.004 kg $ha^{-1}$, respectively) and 8th November 2006 (0.05 ± 0.02 kg $ha^{-1}$ vs 0.005 ± 0.001 kg $ha^{-1}$, P = 0.0257). The repeated measures analyses revealed that total losses were significantly greater from OP than TP (P = 0.0005) over the period of trial (Table 5.9)

Event-wise total losses of $NH_4^+$-N were affected by grazing and urea fertilisation. For example, losses increased on 4th June 2006 from both OP and TP as a result of grazing (0.9 ± 0.29 kg $ha^{-1}$ vs 0.46 ± 0.1 kg $ha^{-1}$, respectively). $NH_4^+$-N losses increased markedly from OP and TP due to urea fertilisation on 17th November 2006 (1.3 ± 0.28 kg $ha^{-1}$ vs 0.3 ± 0.24 kg $ha^{-1}$, respectively) compared with losses in the previous event on 15th November 2006 (0.055 ± 0.01 kg $ha^{-1}$ vs 0.027 ± 0.01 kg $ha^{-1}$, respectively).

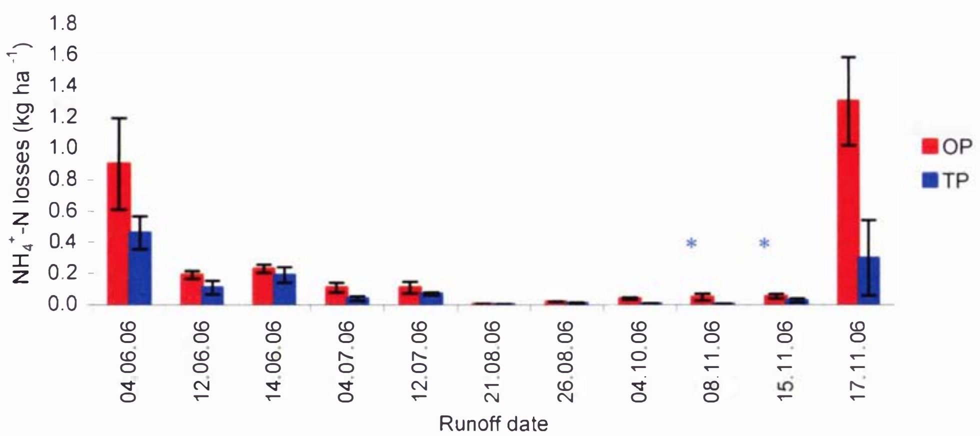

Figure 5.20 $NH_4^+$-N losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

Table 5.9 Least square means of concentrations (mg $L^{-1}$) and losses (kg $ha^{-1}$) of total nitrogen (TN), total kjeldahl nitrogen (TKN), ammonium-N ($NH_4^+$-N) and nitrate-N ($NO_3^-$-N) in surface runoff in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu.

| Treatment | TN | | TKN | | $NH_4^+$-N | | $NO_3^-$-N | |
|---|---|---|---|---|---|---|---|---|
| | conc | loss | conc | loss | conc | loss | conc | loss |
| OP | 4.69 | 0.80 | 4.58 | 0.78 | 1.79 | 0.27 | 0.11 | 0.02 |
| TP | 5.66 | 0.38 | 5.31 | 0.37 | 1.61 | 0.11 | 0.35 | 0.01 |
| SE | | | | | | | | |
| OP | 0.62 | 0.05 | 0.54 | 0.05 | 0.37 | 0.03 | 0.16 | 0.002 |
| TP | 0.45 | 0.03 | 0.39 | 0.03 | 0.26 | 0.02 | 0.12 | 0.001 |
| Sig. | 0.215 | <0.0001 | 0.2852 | <0.0001 | 0.6887 | 0.0005 | 0.2439 | 0.0199 |

$NO_3^-$-N concentrations for most of the events were also below trace level (< 0.25 mg $L^{-1}$) and are not presented. Event-wise traceable values were not significant between treatments (P > 0.05) for any of the runoff events (Figure 5.21). The repeated measures analyses also showed non-significance in $NO_3^-$-N concentrations between treatments (P = 0.2384) over the period of study (Table 5.9). The first traceable $NO_3^-$-N concentrations were measured on 4th June 2006 when runoff occurred after grazing and OP and TP had statistically similar values (0.255 ± 0.005 mg $L^{-1}$ vs 0.64 ± 0.29 mg $L^{-1}$), respectively. However, these values are believed to be as a result of accidental aerial broadcasting of N fertiliser (25 kg $ha^{-1}$) on 25th May 2006. The concentrations increased in the subsequent event on 12th June 2006 in both OP and TP (0.56 ± 0.2 mg $L^{-1}$ vs 3.32 ± 2.36 mg $L^{-1}$), respectively. However, concentrations did not increase immediately after urea fertiliser application in both treatments (Figure 5.21).

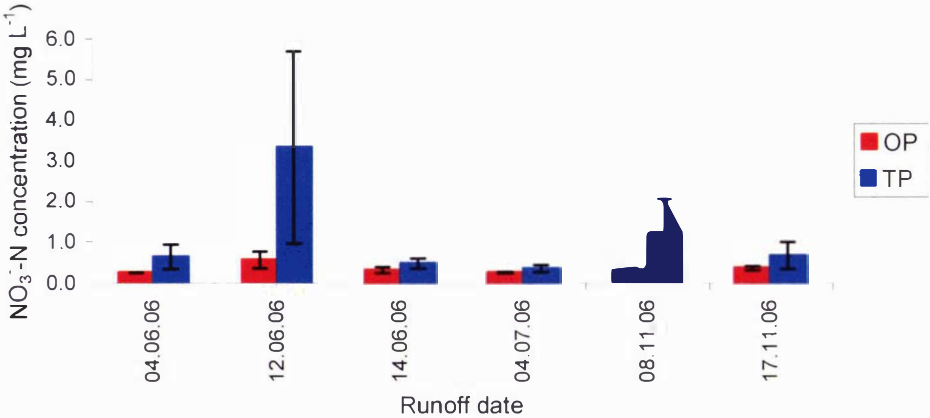


Figure 5.21 $NO_3^-$-N concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

The cumulative $NO_3^-$-N losses (Table 5.8) for the study period were 0.41 ± 0.1 kg $ha^{-1}$ vs 0.27 ± 0.04 kg $ha^{-1}$ from OP and TP ($P = 0.1850$), respectively. Thus $NO_3^-$-N constituted 2.7 % and 3.6 % of the TN losses from OP and TP, respectively. Seasonal losses were restricted to winter and spring 2006 (Table 5.8) only. Similar seasonal trends were observed in both treatments. However, winter losses were significantly higher (82 % vs 78 %) than spring (18 % vs 22 %) from OP and TP, respectively.

The event-wise $NO_3^-$-N losses were only significant between treatments on 4$^{th}$ June 2006 and 8$^{th}$ November 2006 when OP had higher values than TP (0.045 ± 0.0042 kg $ha^{-1}$ vs 0.027 ± 0.0025 kg $ha^{-1}$, $P = 0.0225$, respectively) and (0.03 ± 0.003 kg $ha^{-1}$ vs 0.007 ± 0.002 kg $ha^{-1}$, $P = 0.0039$, respectively) (Figure 5.22). The repeated measures analyses revealed that losses were significantly higher from OP than TP over the study period (Table 5.9).

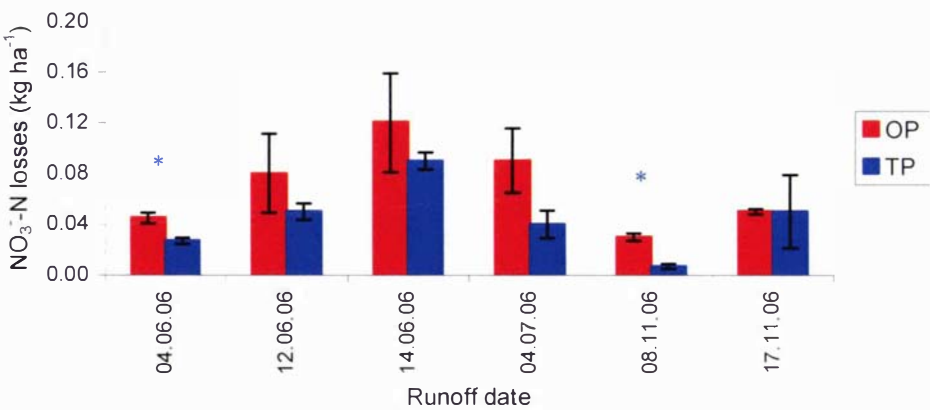


Figure 5.22 Total $NO_3^-$-N losses (kg ha$^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

### 5.3.8 Sheep grazing and camping behaviour.

Sheep grazing and camping behaviour was monitored during the course of the trial. The summer grazing in mid-December 2005 lasted for one week. It was observed that sheep caused substantial damage to both willow and poplar trees in some of the plots. Branches were bent and broken from the main stem (Plate 5.3a), and in a single case the main stem of a willow was found to be broken (Plate 5.3b). These branches did not recover and despite sprouting in the next spring could not be straightened. Sheep grazed the OP plots periodically during the day time but on hot sunny days the sheep preferred to take shelter under the trees (Plate 5.4a). The night camping was also under the trees. This preferred camping resulted in disproportionate accumulation of sheep excreta among TP plots and between treatments. Air dried dung was collected from all plots to quantify the treatment differences. The dung accumulation was significantly greater in TP than OP (1.47 ± 0.12 vs 0.55 ± 0.05 kg Plot$^{-1}$), respectively.

For the early winter grazing, in early June 2006, dung was comparatively better distributed between plots. The day time grazing was relatively evenly distributed but day and night camping was still favoured in the TP plots. This was probably due to some leaves still remaining on the trees (Plate 5.4b) providing shelter to the ewes from dew and frost in the night. As the soil was wet, dung was mashed against the ground surface and isolated dung parts were rarely available. This made it impossible to collect the dung from plots. A survey of plots revealed that tree plots had more dung and urine spots (though very variable among plots) than OP (Plate 5.5a, b). This disparity was later reflected in the nutrient losses from individual plots as well. Apparently, soil disturbance was greater from OP than TP. As a result of rainfall it was observed that surface ponding occurred in all plots but it was more severe in OP than TP.

The spring grazing in early November 2006 also reflected somewhat similar camping behaviour to that in summer 2005. However, tree damage and soil disturbance was minimal, probably due to substantial pasture cover and the sheep included 50 % young lambs that could not substantially harm trees. Also, the dung and urine spots were not as severe as in December 2005 and June 2006. Season, number of ewes and pasture cover affected the grazing consequences in terms of physical damage to the soil and trees and its environmental outcome.


(a)


(b)

Plate 5.3 (a) Tree damage from summer sheep grazing. Broken and bent branches are visible in a tree pasture (TP) plot. (b) Main tree stem broken from summer sheep grazing in a tree pasture (TP) plot at Moginie, Manawatu.

(a)

(b)

Plate 5.4 (a) Day time sheep camping in a tree pasture (TP) plot in summer at Moginie, Manawatu. (b) Early winter sheep grazing in a tree pasture (TP) plot at Moginie, Manawatu.

(a)

(b)

Plate 5.5 (a) A open pasture (OP) plot after winter sheep grazing. Dung and urine spots are not visible at Moginie, Manawatu. (b) A tree pasture (TP) plot after winter sheep grazing. Dung and urine spots are visible at Moginie, Manawatu.

## 5.3.9 DRP concentrations in soil water samples from suction cups

DRP concentrations in soil water samples from suction cups were not significantly different between treatments throughout the study period. At the start of the experiment, concentrations were quite low. For example, concentrations on 22$^{nd}$ September 2005 (when measured first) were low and similar from OP and TP (0.034 ± 0.007 mg $L^{-1}$ and 0.032 ± 0.005 mg $L^{-1}$, respectively). Later on, the concentrations decreased even further and were at the lowest level of environmental concern (0.01 mg $L^{-1}$) on 5$^{th}$ October 2006 (Figure 5.23).

The P fertiliser application increased the DRP concentrations in drainage water in both treatments. For example, on 1st April 2006 DRP concentrations increased substantially from OP and TP (0.97 ± 0.34 mg $L^{-1}$ and 1.31 ± 0.632 mg $L^{-1}$, respectively). The post-fertiliser event on 24th October 2006 also showed some increase in DRP concentrations in soil water samples but it was mainly restricted to TP (Figure 5.23). The post-grazing event on 4th June 2006 did not result in any significant increase in the DRP concentrations in the soil water samples (Figure 5.23). Nevertheless, concentrations remained higher than the required level for aquatic weed growth in all post-fertiliser and grazing events. The repeated measures analyses revealed that differences in concentrations were non-significant between treatments (P > 0.05).

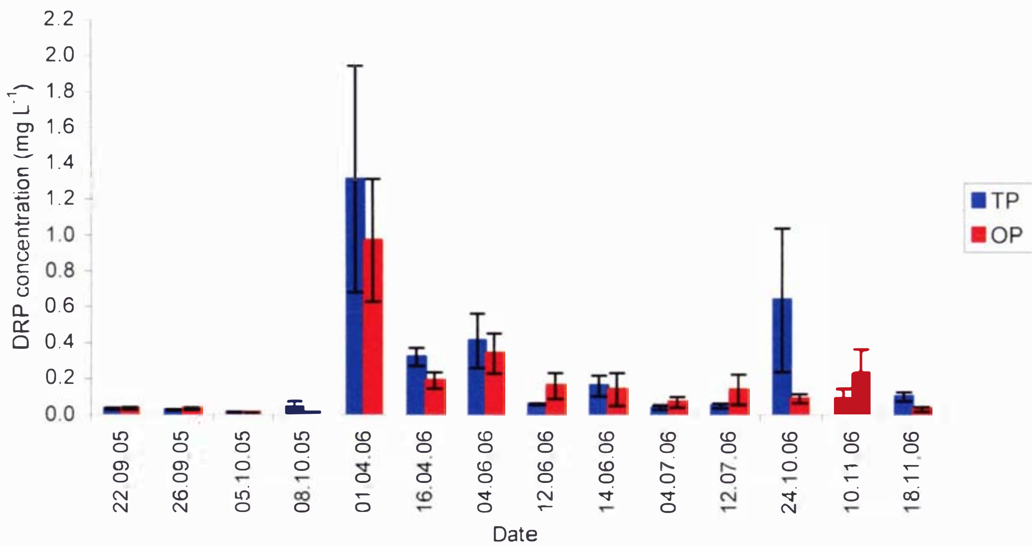


Figure 5.23 DRP concentrations (mg $L^{-1}$) in soil water samples taken from suction cups in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment.

## 5.3.10 Nitrogen concentrations in soil water samples from suction cups

The $NH_4^+$-N concentrations remained below the detectable level throughout the study period except in the post-urea application event on 17th November 2006, but concentrations were similar between OP and TP (2.1 ± 0.28 mg $L^{-1}$ and 2.3 ± 0.37 mg $L^{-1}$, respectively). $NO_3^-$-N concentrations were not detectable throughout the study period.

## 5.4 Results (Riverside experiment)

### 5.4.1 Surface runoff

The cumulative surface runoff at Riverside Farm for the study period was similar ($P = 0.8443$) between OP and WP (28.8 ± 1.30 mm and 31.4 ± 1.94 mm, respectively). Marked variability between individual plots led to the non-significant differences between treatments (CV = 39 %).

During spring 2005, differences in the quantity of event-wise runoff were also not significant between treatments. However, during summer, WP did not yield any runoff but OP had runoff on three occasions (Figure 5.24). Due to very small events on 22nd December 2005 and 10th February 2006, differences were not significant despite no runoff in WP but OP had significantly higher ($P = 0.0098$) runoff on 4th January 2006 compared with WP (6.8 ± 0.05 mm and 0.00 mm, respectively).

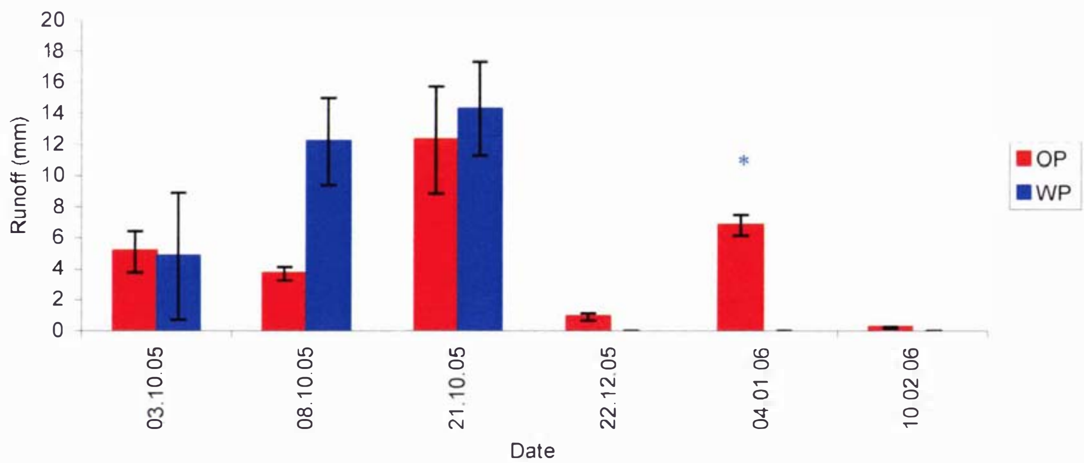


Figure 5.24 Event-wise surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, Masterton. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

During winter 2006, variability in WP plots were unexpectedly high and runoff data were not matched with rainfall. Despite remedial measures, the runoff in WP could not be reconciled with rainfall. This indicated that WP plots were receiving subsurface water from the hilly terrain behind them. Water was moving from the hills and coming to the surface inside the plots thereby contributing the additional runoff that surpassed the actual rainfall total. Therefore, winter data could not be meaningfully interpreted and measurements were ceased.

### 5.4.2 Sediment load in surface runoff

The TSS concentrations were highest on 8th October 2005 (Figure 5.25) when OP had significantly higher values ($P = 0.0299$) than WP ($117 \pm 9$ mg $L^{-1}$ vs $61.5 \pm 3.7$ mg $L^{-1}$, respectively). However, in the last two events on 22nd December 2005 and 4th January 2006, WP did not yield any sediment but significantly higher values were recorded from OP ($108 \pm 12.9$ mg $L^{-1}$, $P = 0.0141$ and $58 \pm 8.4$, $P = 0.0202$, respectively).

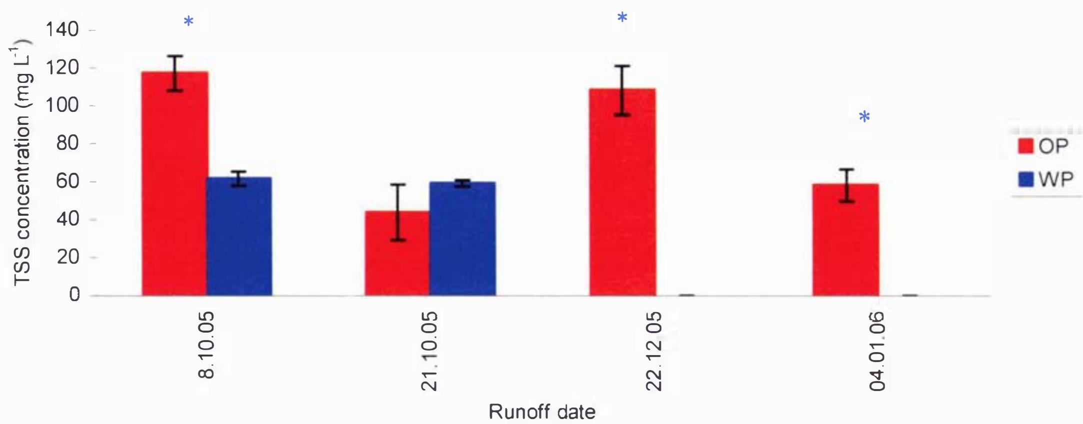


Figure 5.25 Total suspended solids (TSS) concentrations (mg $L^{-1}$) in surface runoff in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, Masterton. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

The repeated measures analysis revealed that TSS concentrations were significantly higher from OP than WP (Table 5.10) over the study period ($P < 0.0001$). Similarly, ISS and OSS concentrations were also significantly higher ($P = 0.0004$) from OP than WP over the study period (Table 5.10).

The total cumulative TSS losses were similar ($P = 0.6175$) between OP and WP ($14.1 \pm 0.9$ kg $ha^{-1}$ and $15.8 \pm 2.8$ kg $ha^{-1}$, respectively). The total cumulative ISS losses were also similar ($P = 0.1863$) between OP and WP ($10.2 \pm 0.21$ kg $ha^{-1}$ and $12.39 \pm 1.07$ kg $ha^{-1}$, respectively) while the OSS contributions ($P = 0.8425$) were only $3.9 \pm 0.77$ kg $ha^{-1}$ and $3.47 \pm 1.73$ kg $ha^{-1}$, respectively).

Therefore, ISS contributions were about 72 % and 78 % while OSS constituted 28 % and 22 % of TSS losses from OP and WP, respectively.

Table 5.10 Least squares means for suspended solids concentrations (mg $L^{-1}$) and losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and willow pasture (WP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | TSS | | ISS | | OSS | |
|---|---|---|---|---|---|---|
| | conc | losses | conc | losses | conc | losses |
| OP | 81.77 | 3.53 | 59.97 | 2.56 | 21.8 | 0.97 |
| WP | 30.16 | 3.96 | 23.84 | 3.10 | 6.31 | 0.86 |
| SEM | 4.15 | 0.39 | 4.47 | 0.2079 | 1.86 | 0.27 |
| Significance | <0.0001 | 0.4612 | 0.0004 | 0.1016 | 0.0004 | 0.7829 |

The event-wise losses for TSS (Figure 5.26) were similar between treatments except on 22nd December 2006 when OP had significantly higher losses (P = 0.0198) compared with WP (0.97 ± 0.13 kg $ha^{-1}$ and 0.00 kg $ha^{-1}$, respectively). The repeated measures analysis revealed that TSS losses remained similar (P = 0.4612) between treatments over the time of study (Table 5.10). Similar to TSS, the event-wise ISS and OSS losses were also statistically similar (repeated measures analyses) between OP and WP (P = 0.1016, P = 0.7829), respectively (Table 5.10).

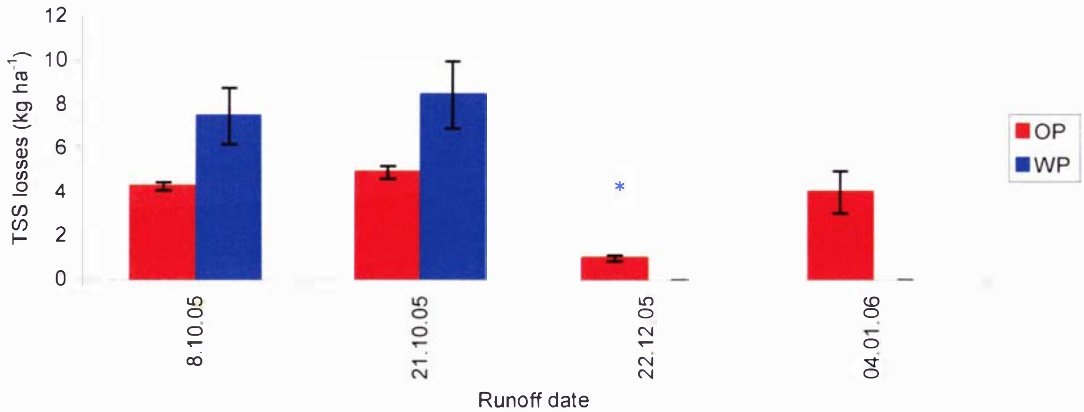


Figure 5.26 Total suspended solids (TSS) losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

### 5.4.3 Phosphorus losses in runoff water

Event-wise total P concentrations (Figure 5.27) were similar between treatments except on 4th January 2006 when OP had significantly higher values ($P = 0.0429$) than WP (2.71 ± 0.58 mg $L^{-1}$ and 0.00 mg $L^{-1}$, respectively). Although concentrations from OP were at their highest on 22nd December 2005 and there was a zero concentration in WP due to no surface runoff (3.98 ± 2.1 mg $L^{-1}$ and 0.00 mg $L^{-1}$), the difference in values between treatments was non-significant due to marked variability from OP plots (CV = 106 %).

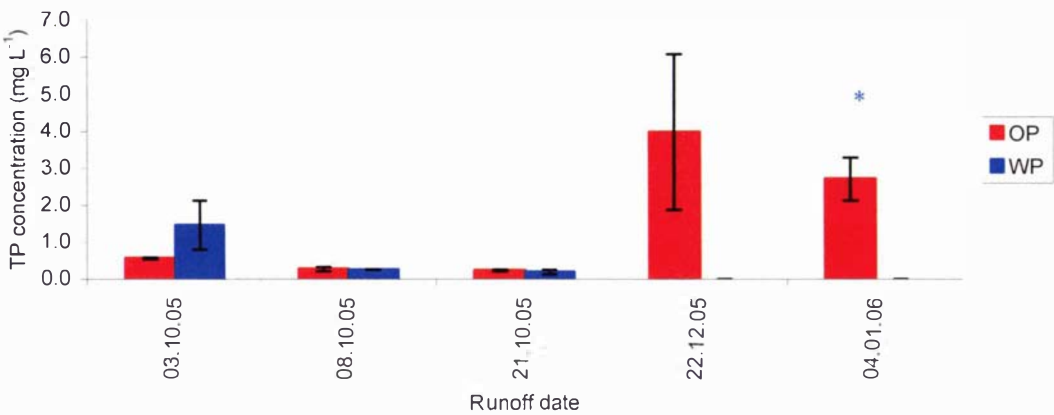


Figure 5.27 Total P concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

Such variability was probably as a result of differential dung deposition in individual OP plots. However, repeated measures analysis revealed that total P concentrations were significantly greater ($P = 0.0282$) from OP than WP over the study period (Table 5.11).

The cumulative total P losses were similar between OP and WP (0.27 ± 0.06 kg $ha^{-1}$ and 0.10 ± 0.05 kg $ha^{-1}$, respectively). Event-wise losses of P from treatments were also not significant ($P > 0.05$) for all the events (Figure 5.28). The highest losses from OP were recorded on 4th January 2006 and despite no losses in WP, the values were not significantly different between treatments due to marked variability in the individual OP plots (0.18 ± 0.06 kg $ha^{-1}$ vs 0.00 kg $ha^{-1}$). However, repeated measures analysis showed that total P losses were significantly higher ($P = 0.0199$) from OP than WP, respectively (Table 5.11).

Table 5.11 Least squares means for total P and DRP concentrations (mg $L^{-1}$) and losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and willow pasture (WP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | TP | | DRP | |
|---|---|---|---|---|
| | conc | losses | conc | losses |
| OP | 1.55 | 0.056 | 0.15 | 0.00724 |
| WP | 0.38 | 0.019 | 0.09 | 0.00758 |
| SE | | | | |
| OP | 0.32 | 0.009 | 0.24 | 0.00149 |
| WP | 0.32 | 0.009 | 0.24 | 0.00149 |
| Significance | 0.0282 | 0.0199 | 0.1245 | 0.8748 |

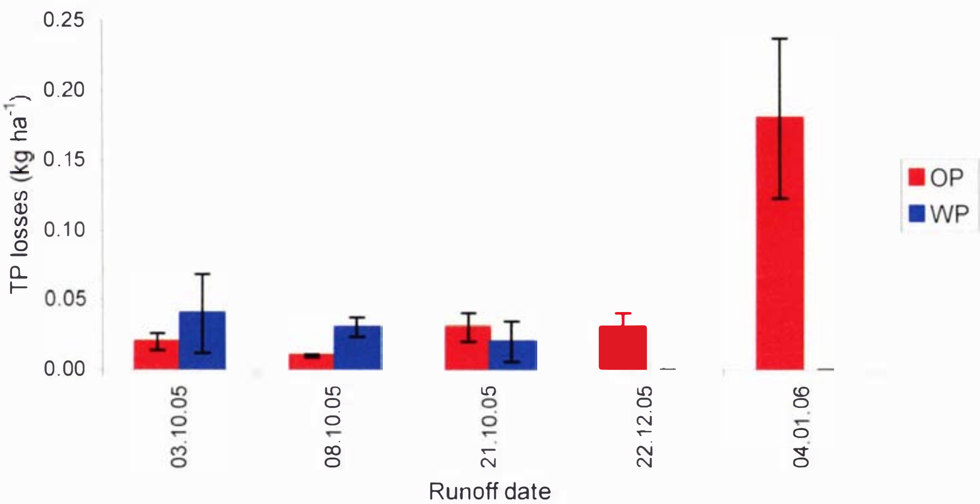


Figure 5.28 Total P losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment.

The event-wise DRP concentrations (Figure 5.29) were significantly different ($P = 0.0069$) between treatments on 4th January 2006 when OP had higher values than WP (0.12 ± 0.01 mg $L^{-1}$ and 0.00 mg $L^{-1}$, respectively). Like the total P, DRP mean concentrations from OP were at their highest on 22nd December 2005 and were zero in WP (0.25 ± 0.1 mg $L^{-1}$ vs 0.00 mg $L^{-1}$), but differences were not significant ($P = 0.2623$) due to marked variability from OP plots (CV = 129 %). The repeated measures analysis also showed non-significant differences (Table 5.11) in DRP concentrations between treatments (P = 0.1245).

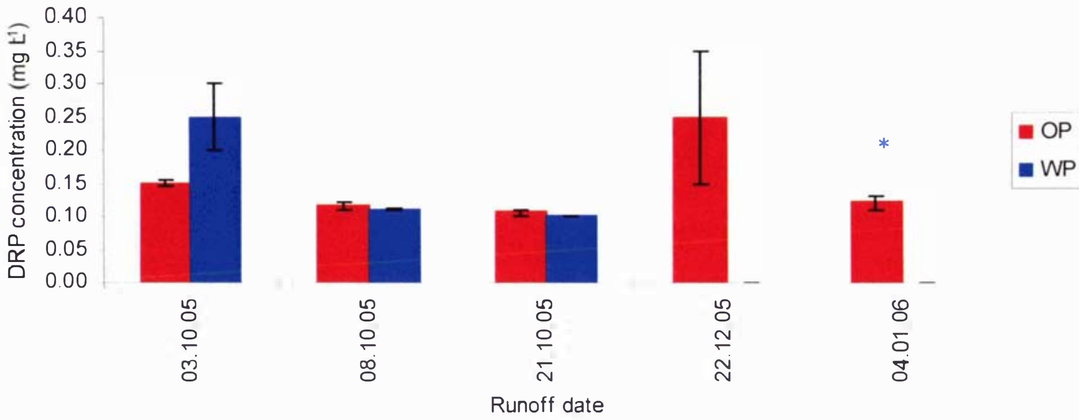


Figure 5.29 DRP concentrations (mg $L^{-1}$) in surface runoff in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

The cumulative DRP losses were statistically similar (P = 0.8075) between OP and WP (0.035 ± 0.009 kg $ha^{-1}$ and 0.037 ± 0.014 kg $ha^{-1}$, respectively). Therefore, the DRP contribution to total P losses was 13 % and 37 % from OP and TP, respectively. The event-wise losses were similar (Figure 5.30) between treatments except on 4th January 2006 when OP had higher losses (P = 0.0003) than WP (0.008 ± 0.001 kg $ha^{-1}$ and 0.00 kg $ha^{-1}$, respectively). The time series analysis (repeated measures) also showed non-significant differences (Table 5.11) between treatments (P = 0.8748).

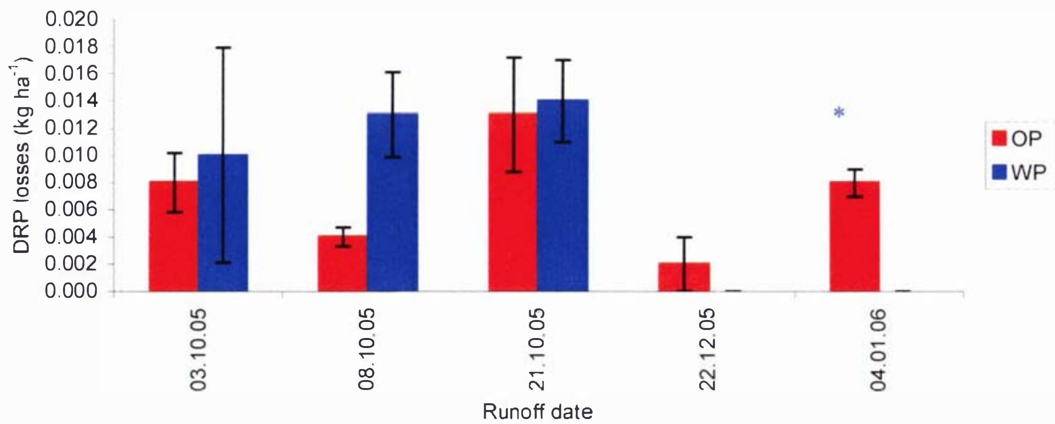


Figure 5.30 DRP losses (kg $ha^{-1}$) in surface runoff in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

### 5.4.4 Nitrogen losses in runoff water

Since $NO_3^-$-N concentrations were not detectable throughout the study period, TKN values are presented as TN (Figure 5.31). Event wise TN concentrations were not significantly different between treatments except on 8th October 2005 when OP TN concentration was significantly higher (P = 0.0374) than WP (4.58 ± 0.41 mg $L^{-1}$ and 2.5 ± 0.001 mg $L^{-1}$, respectively). Like total P and DRP concentrations, mean TN concentration from OP was also highest on 22nd December 2005 but large variability in the individual OP plots (CV = 105 %) led to non-significant differences between OP and WP (40.63 ± 21.45 mg $L^{-1}$ and 0.00 mg $L^{-1}$, respectively). The repeated measures analysis also confirmed non-significance of TN concentrations between treatments over the study period (Table 5.12, P = 0.2393).

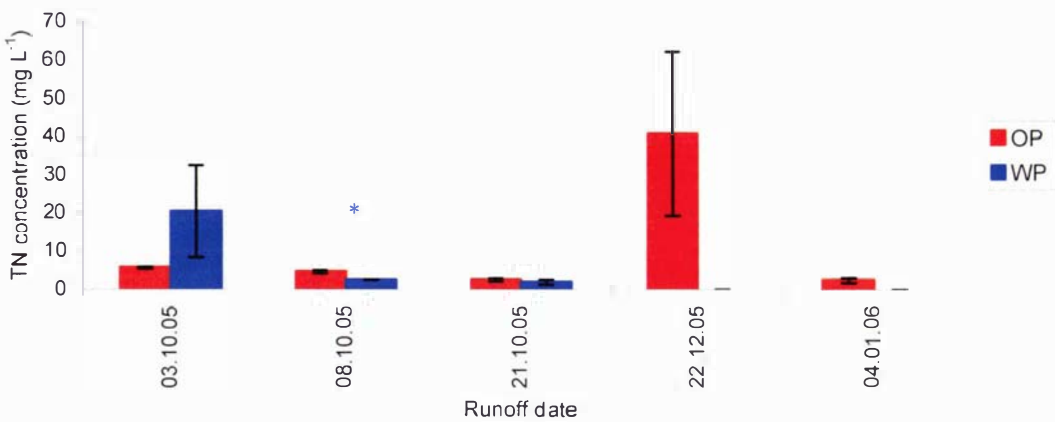


Figure 5.31 TN concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.

The cumulative TN losses over the study period were similar (P = 0.7532) for OP and WP (1.23 ± 0.07 kg $ha^{-1}$ and 1.07 ± 0.47 kg $ha^{-1}$, respectively). The event-wise losses were only significantly different between treatments on 4th January 2006 (P = 0.0377) when OP had higher losses than WP (0.15 ± 0.02 kg $ha^{-1}$ and 0.00 kg $ha^{-1}$, respectively).

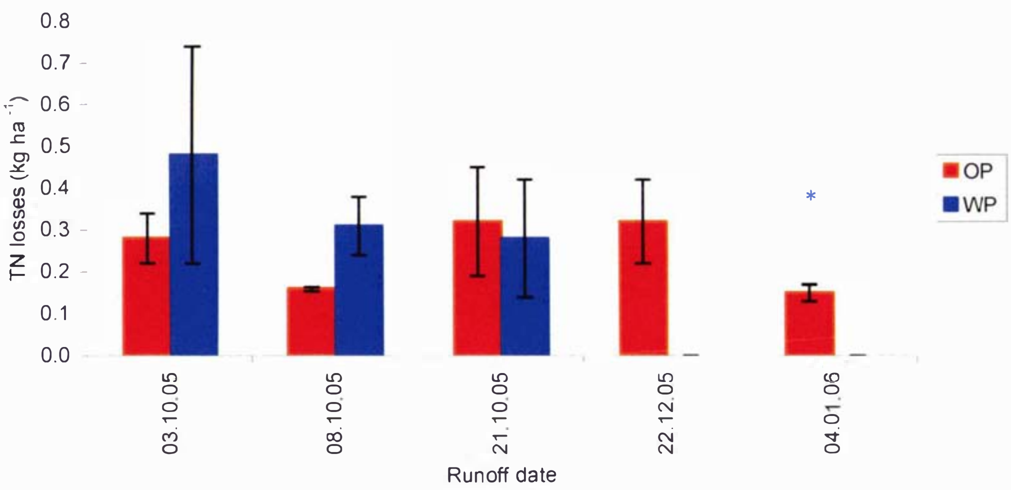


Figure 5.32 TN losses (kg $ha^{-1}$) in surface runoff in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

The losses on 3rd October 2005 (0.28 ± 0.06 and 0.48 ± 0.26) and 21st October 2005 (0.32 ± 0.13 and 0.28 ± 0.14) were among the major contributors of all the events from OP and WP (Figure 5.32), respectively.

Repeated measures analysis revealed that differences in TN losses were non-significant over time between treatments (Table 5.12, P = 0.1988).

Table 5.12 Least squares means for total nitrogen (TN) and ammonium-N ($NH_4^+$-N) concentrations (mg $L^{-1}$) and losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and willow pasture (WP) treatments at Riverside Farm near Masterton, Wairarapa.

| Treatment | TN | | $NH_4^+$-N | |
|---|---|---|---|---|
| | conc | losses | conc | losses |
| OP | 11.12 | 0.250 | 1.02 | 0.043 |
| WP | 4.95 | 0.216 | 1.93 | 0.060 |
| SEM | 3.49 | 0.051 | 0.68 | 0.023 |
| Significance | 0.2393 | 0.6481 | 0.3837 | 0.6270 |

The $NH_4^+$-N concentrations were only detectable for three events over the study period (Figure 5.33). The event-wise concentrations were significant between treatments (P = 0.0111) on 8th October 2005 when OP had higher value than WP (0.5 ± 0.025 mg $L^{-1}$ and 0.26 ± 0.005 mg $L^{-1}$, respectively).

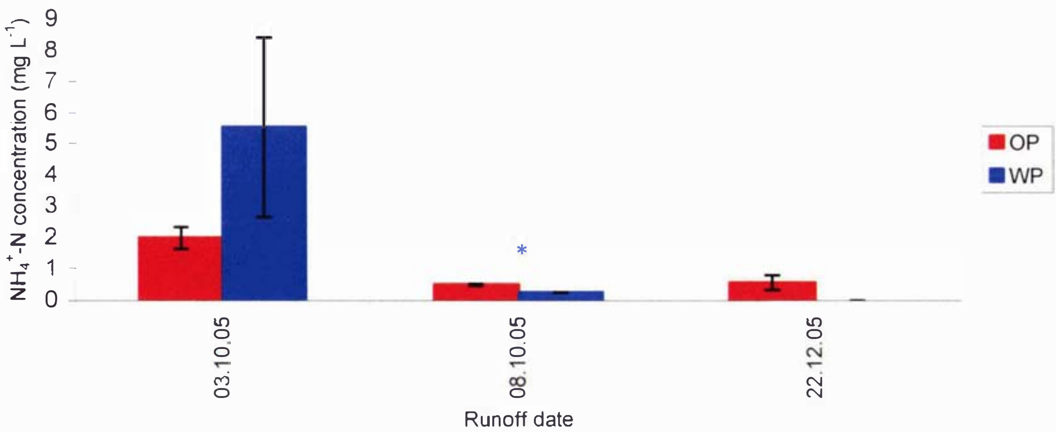


Figure 5.33 $NH_4^+$-N concentrations (mg $L^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

The highest concentrations were on 3rd October 2005 from OP and WP (1.98 ± 0.35 mg $L^{-1}$ and 5.53 ± 2.88 mg $L^{-1}$, respectively). The repeated measures analysis showed that differences in concentrations between treatments were non-significant over time (Table 5.12, P = 0.3837).

The cumulative $NH_4^+$-N losses were similar between OP and WP (0.133 ± 0.045 kg $ha^{-1}$ and 0.182 ± 0.098 kg $ha^{-1}$, respectively). The event-wise differences in losses between treatments (Figure 5.34) were significantly different (P = 0.0267) on 22nd December 2005 when OP had a higher value than WP (0.005 ± 0.0008 kg $ha^{-1}$ and 0.00 kg $ha^{-1}$, respectively). The repeated measures analysis revealed that losses were not significant over the time of study between treatments (Table 5.12, P = 0.6270).

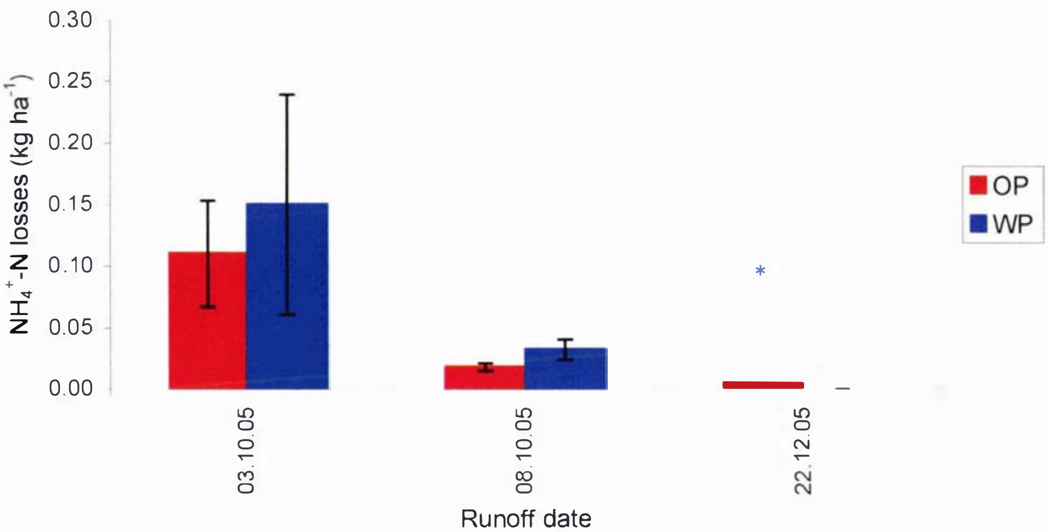


Figure 5.34 $NH_4^+$-N losses (kg $ha^{-1}$) in surface runoff (mm) in open pasture (OP) and tree pasture (WP) treatments at Riverside Farm, near Masterton, Wairarapa. Line bars show the SEM for each treatment. * denotes significance at $P < 0.05$.

# 5.5 Discussion

## 5.4.1 Effect of trees on soil moisture, runoff and sediment

At the Moginie experimental site the willow and poplar trees increased the soil moisture deficit in the top 0-150 mm soil depth during summer and autumn months. There was also a trend for soil moisture to be lower in the deeper soil depths in TP than OP. The variability in soil moisture in the lower soil depths was more obvious in TP than OP. Such variability in the tree treatment was probably a result of the differential rooting systems of willow and poplar. The rooting ability and root development of trees are under strong genetic control (Stokes et al., 1997). Willow generally have a mat-like fibrous rooting system concentrated near the soil surface while poplar have rope like roots (Wilkinson, 1999) that may penetrate deeper than fibrous roots. The horizontal and vertical growth and distribution of fine roots also differ between tree species (Jonsson et al., 1988; Nambiar, 1983).

The soil moisture deficit created through evapotranspiration along with rainfall interception in a silvopastoral system involving fast growing trees such as willow and poplar can affect the surface runoff. Being small trees (3-4 yrs), willow and poplar in this particular experiment (Moginie) were not very effective at ameliorating the quantities of runoff in big storms such as on 5$^{th}$ October 2005 and 22$^{nd}$ October 2006 but their effect on runoff was more pronounced in some of the smaller events. At Riverside Farm, coppice willow were also not effective in reducing runoff in spring due to their small size. At Moginie, winter 2006 yielded significantly greater (41.6 % vs 41.6 %) runoff compared with spring 2006 (26.7 % vs 22.2 %) in both OP and TP. This was probably due to lack of vegetative cover and more frequent rainfall events in winter than spring (9 vs 5, respectively) capable of initiating runoff. The winter runoff as a proportion of rainfall was higher from OP (48 %) than TP (26 %). Quinn & Stroud (2002) also reported that surface runoff from pasture as a proportion of rainfall was highest in winter (78 %) followed by spring (47 %). The very high proportion of runoff in Quinn & Stroud's (2002) study was due to different topography of the area where slope varied from steep (>30$^{o}$) to hilly (17-20$^{o}$).

In the current study, trees were more effective in reducing runoff as they aged. For example, in spring 2006, the significant differences in runoff between TP and OP were more obvious than spring 2005. Previous studies of surface runoff under trees have shown that trees can be effective at reducing runoff from a very young age. For example, Van et al., (1980) studied the effect of afforestation on streamflow in South Africa and reported that *Eucalyptus grandis* exerted an observable influence from the third year after planting, with a maximum apparent reduction in flow, expressed as rainfall equivalent, of between 300 and 380 mm $yr^{-1}$. The seasonal effect was greatest in summer with maximum reduction of 200-260 mm $yr^{-1}$ and 100-130 mm $yr^{-1}$ in winter.

Similarly, Bosch & Hewlett (1982) in their review of 94 catchments experiments showed that Pine and Eucalypt forest types cause on average 40 mm and deciduous hardwood 25 mm change in water yield per 10 % change in cover. Although soil moisture data show that trees in the current experiment could have been more effective in summer than any other season, sufficient rainfall is rare to initiate runoff from flatter slopes in summer in the North Island, New Zealand. Descheemaeker et al., (2006) reported a positive correlation between the runoff generating rainfall threshold and vegetative cover, and at 65 % vegetative cover, runoff could be negligible. This was true for the Riverside site in the summer of 2005-06 when WP did not yield any runoff on three occasions due to vegetative cover as grass was not removed after September 2005 and also willow were not grazed at all.

The cumulative TSS losses over the study period at Moginie were significantly greater ($P = 0.0158$) from OP than TP (442.5 ± 67.2 kg $ha^{-1}$ and 212.1 ± 27.9 kg $ha^{-1}$, respectively) but coppice willow, due to their small size, had TSS losses similar to OP at Riverside Farm. Substantial vegetative cover is thought to be the best trap for sediment in the event of rainfall capable of initiating runoff. Quinn & Stroud (2002) reported 988 kg $ha^{-1}$ $yr^{-1}$ of SS from a pasture catchment while losses from native forest were 320 kg $ha^{-1}$ $yr^{-1}$ in New Zealand. Arifeen & Chaudhry (1998) also reported greater sediment losses from a rangeland sub-catchment compared with forestry sub-catchment ( 340 kg $ha^{-1}$ and 158 kg $ha^{-1}$ respectively) situated in a moist temperate area in Pakistan. However, losses vary depending on slope and the type and degree of vegetative cover. For example, Bartley et al., (2006) reported 60 times more sediment loss from hillslopes with bare patches compared with slopes having relatively high mean vegetative cover in Australia.

Investigations into the effect of individual plants (shrubs) of different species on runoff and soil erosion also revealed promising results with differential effects depending on type of species and other morphological characteristics such as canopy size and crown shape. For example, Bochet et al., (2006) compared *Rosmarinus*, *Stipa* and *Anthyllis* canopies in east Spain and reported that cumulative soil loss was reduced by 94.3 %, 88.0 % and 30.2 %, and cumulative runoff volume was reduced by 66.4 %, 50.8 % and 18.4 % under the *Rosmarinus*, *Stipa* and *Anthyllis* canopies, respectively, compared with a bare surface. Experimental studies on riparian buffers have also shown the effect of vegetative cover on runoff and sediment reduction. Schoonover et al., (2006) studied the filtering capability of giant cane (*Arundinaria gigantea)* and forest riparian buffers in southern Illinois, USA. Results showed 86 % sediment reduction over 6.6 m of forest buffer while reduction by giant cane was even higher (94 % over 3.3 m).

### 5.4.2 Effect of grazing on sediment and nutrient losses

At Moginie experimental site, winter grazing increased TSS concentrations in runoff from both OP and TP treatments compared with pre-grazing runoff event. The comparative increase in concentrations was greater from OP than TP (TSS = 368 ± 60.38 mg $L^{-1}$ and 208 ± 18.17 mg $L^{-1}$, respectively) when compared with pre grazing concentrations on 16$^{th}$ April 2006 (14.5 ± 10.3 mg $L^{-1}$ vs 10 ± 0.68 mg $L^{-1}$, respectively). The results are supported by Elliot & Carlson (2004) who reported a concentration of 394 mg $L^{-1}$ of SS in a post-winter grazing event compared with a pre-grazing event concentration of 30.5 mg $L^{-1}$ from pastoral land in New Zealand. Smith (1987) has shown a strong inverse relationship between sediment loss and grass length for a sheep grazed pasture in Waikato, suggesting that grazing will increase the concentration of contaminants in runoff due to removal of grass. Other studies of the effects of cattle and sheep grazing and treading on soil physical and chemical properties in New Zealand also suggest that sediment load may increase as a result of grazing. For example, Sheath and Carlson (1998) reported that soil surface damage (soil disturbance and puddling) was greatest on animal tracks and camping locations (cattle and sheep). Apart from puddling and soil disturbance, grazing results in plant disruption, burial of leaves and reduction in tiller numbers and vigour (Edmond, 1962) that may lead to increased runoff and sediment loss, especially in winter.

Nguyen et al., (1998) have also reported increased SS concentrations as a result of cattle treading but losses were higher in steep inter-track plots (814 ± 162.8 g $m^{-3}$) than easy contoured plots (356 ± 45.5 g $m^{-3}$). Similarly, Adams & Elliott (2006) using simulated rainfall experiments showed that the mass of suspended sediment increased as a result of grazing due to direct raindrop effect instead of overland flow detachment. Therefore, the authors advised that grazing cattle or sheep on steeply sloping hill country paddocks, especially in winter, should be carefully managed to limit the transport of sediment into watercourses.

The greater SS losses in the post-winter grazing event on 4$^{th}$ June 2006 from OP than TP suggested that the soil in OP was subjected to more severe disturbance than TP. It appears that tree roots contribute to increased infiltration and decreased soil compaction by helping to bear the weight of sheep. Also, the significantly higher soil moisture status in OP than TP in the upper 0-150 mm soil depth as measured on 31$^{st}$ May 2006 may have contributed to increased runoff and sediment loss from OP than TP. Carrol et al., (2004) from the UK, reported up to 60 times higher infiltration rates in areas planted with trees than in adjacent grazed pastures and significant differences were also observed for soil moisture. Bochet et al., (2006) reported that rainfall intensity and soil water status prior to rainfall strongly influenced runoff and soil loss rates. Similar findings have been reported by Meyles et al., (2003) with regard to the relationship of soil moisture to runoff in the Netherlands.

The impact of sheep grazing on SS losses in runoff persisted over the winter but reduced with time so that sediment losses in spring from both OP and TP were minimal. This was expected because plots were not grazed from the June

2006 event until early November 2006 and pasture growth provided a good ground cover against the rainfall impact. Sheath & Carlson (1998) also reported that evidence of initial impact of winter grazing on SS loss in surface runoff disappeared over the spring and this process was more rapid in sheep grazed paddocks than dairy cattle.

Nutrients concentrations and total losses in surface runoff from both OP and TP increased as a result of sheep grazing. Winter grazing had a greater effect than spring grazing. The post-winter grazing concentrations for total P (51.11 ± 1.6 mg $L^{-1}$ vs 56.91 ± 7.35 mg $L^{-1}$) and TN (15.88 ± 0.63 mg $L^{-1}$ vs 18.04 ± 2 mg $L^{-1}$) were substantially higher than the post-spring grazing total P (3.5 ± 0.15 mg $L^{-1}$ vs 13.35 ± 6.25 mg $L^{-1}$) and TN (3.85 ± 0.27 mg $L^{-1}$ vs 7.85 ± 2.69 mg $L^{-1}$) from OP and TP, respectively. This was partly due to removal and reduced regrowth of pasture in winter. Also, spring grazing was not hard and with sheep consuming less than 50 % of the grass contributed to the minimal movement of sediment and nutrients. Previous studies have shown that hard grazing increases the likelihood of high concentrations of nutrients in runoff (McColl & Gibson, 1979) and drainage (Houlbrooke et al., 2004). Trees were not effective in reducing total P losses in post-grazing events in winter and spring, partly due to preferred camping under trees. However, DRP losses were significantly smaller in the post-grazing event in spring. The TN losses were significantly smaller in both winter and spring post-grazing events.

Quinn & Stroud (2002) suggested that measures to control P loss need to focus on land management activities such as tree planting to control erosion. They reported minor DRP contribution (9-19 %) to the total P export from pasture and mixed land-use catchments at Whatawhata while the DRP contribution was a much higher (63 %) component of the total P from Toenepi pasture catchment, the latter being treated with dairy shed treatment systems that represented a point source with less erosion. The Whatawhata site was steeper than Toenepi and P export was mainly in the form of particulate P.

The immediate post grazing $NH_4^+$-N concentrations at Moginie tended to be higher than $NO_3^-$-N. For example, $NH_4^+$-N concentrations on 4th January 2006 (5.32 ±1.34 mg $L^{-1}$ vs 7.52 ± 1.22 mg $L^{-1}$) were higher than $NO_3^-$-N (0.25 ± 0.005

mg $L^{-1}$ vs 0.64 ± 0.29 mg $L^{-1}$) from OP and TP, respectively. Although the same was true for the spring post-grazing runoff event on 8th November 2006 from OP, $NO_3^-$-N concentrations surpassed $NH_4^+$-N in TP. The differences could be attributed to differential urine spots from OP and TP that produced more $NO_3^-$-N over time in TP than $NH_4^+$-N due to nitrification of ammonium. The results were in line with the findings of Smith & Monaghan (2003) who reported that losses of $NH_4^+$-N in post-grazing surface runoff were greater than $NO_3^-$-N which was attributable to grazing pressure creating soil treading damage during moist soil conditions. Houlbrooke et al., (2004) also reported a similar trend for a dairy cattle grazing trial in Manawatu, North Island, New Zealand. Similarly, McColl & Gibson (1979) reported that post grazing $NO_3^-$-N concentrations peaked after about two weeks when TKN concentrations declined from peak, suggesting that $NO_3^-$-N concentrations probably depended on nitrification of ammonium from dung and urine.

### 5.4.3 Sheep camping behaviour and dung distribution

In the present study, it was observed that sheep tend to camp under trees, especially on hot sunny days and resulted in significant deposition of dung and urine under willow and poplar trees. This raises a serious question about the role of trees to mitigate environmental pollution in silvopastoral systems. Although total amount of sheep excreta will not increase on a farm basis but its distribution is of concern because the nutrients from the dung and urine may not be utilised efficiently and most of them may end up in rivers and streams before their consumption by trees and pasture plants. The other important consideration is that willow and poplar become leafless in winter and the dung and urine patches concentrated around such trees will be fully exposed to rainfall impact and become a point source for aquatic pollution. Therefore, farm managers will have to determine tree density that can address this issue.

Previous studies have noted the behaviour of sheep camping and its pros and cons. It is well established that sheep tend to take shelter under trees on warm sunny days for shade and shelter (Arnold & Pahl, 1974; Squires, 1975; Taylor & Hedges, 1984). During mid day, sheep camping can extend to lengthy periods in the shade of trees (Hilder & Mottershead, 1963; Squires, 1975) and sheep can be very selective of the tree species for their camping (Bowns, 1971). Taylor & Hedges (1984) reported from the temperate region of New South Wales, Australia, that Merinos preferred large trees with a high canopy/bole ratio. This indicates that willow may be preferred for camping than poplar. Nevertheless, in New Zealand, shade and shelter can be beneficial to reduce the lamb mortality and overall sheep health (Pollard, 2006).

### 5.4.4 Effect of fertiliser application on nutrient losses in runoff

In the current study, P fertiliser application at Moginie increased the total P and DRP concentrations and total losses in both treatments. However, the amount and type of fertiliser, pre application soil moisture status and total runoff affected the concentrations. The post autumn SSP fertiliser (P = 45 kg $ha^{-1}$) application concentrations were considerably lower than spring fertiliser application (P = 50 kg $ha^{-1}$) due to greater runoff volume in the autumn than the spring event. Runoff volume affected the dilution rates leading to differential concentrations between autumn and spring events in 2006. Past research has shown that nutrient concentration can be affected by runoff volume or nutrient uptake by plants. For example, McColl & Gibson (1979) reported low P concentrations in winter because of dilution and low in spring because of vigorous uptake by plants. Runoff occurred within hours after P fertiliser application in spring and plant uptake would not have affected the concentrations in the current study.

Difference in soil moisture status at the time of fertiliser application in autumn and spring are also believed to have some impact on rate and extent of P mobilisation. In Victoria Australia, Nash et al., (2004) studied the P mobilisation from SSP and Diammonium Phosphate (DAP) fertilisers and reported total dissolved phosphorus (TDP) concentrations were higher in the wetting front than the rear front and the rapidly infiltrating water at the wetting front in overland flow is likely to carry P with it mobilized at the soil surface, and P infiltration will be proportional to mobilisation rates. The results from the Nash et al., (2004) study indicate that a higher soil moisture deficit can cause greater infiltration of P until the soil is saturated and runoff is initiated. This was probably true in the post P fertiliser application event in autumn 2006 when soil moisture deficit probably caused higher P losses in drainage than in runoff while the reverse seems true in the post-fertiliser event in spring 2006.

Contrary to the autumn of 2006, spring fertiliser application was at a time when soil was close to field capacity due to the rainfall capable of initiating runoff event on 22$^{nd}$ October 2006. The higher soil moisture status followed by rainfall probably increased the fertiliser mobilisation and export in runoff water despite a smaller event compared with autumn. Nevertheless, from the environmental point of view, total P and DRP concentrations increased to unacceptable levels in both events.

A review of a number of single landuse catchment studies in New Zealand by Wilcock (1986) concluded that large quantities of P are transported to surface waters due to storm runoff occurring just after fertiliser applications. Nash and Murdoch (1997) reported that erosion or movement of surface soil particles was not believed to be the major process by which P loss occurred as 91 % of the total 3.2 kg P ha$^{-1}$ lost was in the dissolved form. It was suggested that the dissolved form of P was as a result of dissolution process at the soil surface. Furthermore, research in Victoria Australia by Nash et al., (2000) found that days since fertilizing was inversely related to total P concentrations in runoff water whereas days since grazing was only weakly related to total P concentrations, suggesting that livestock did not mobilise large stores of P relative to fertilization. Lambert et al., (1985) also concluded that increases in fertiliser application on New Zealand hill country can increase nutrient loading in runoff waters resulting in accelerated eutrophication.

The late autumn N fertiliser (Crop Master 13) application on 25$^{th}$ May 2006 (N = 25 kg ha$^{-1}$) did not increase TN concentrations in the subsequent runoff event on 29$^{th}$ May 2006. However, a small event on 27$^{th}$ May 2006 that did not yield enough runoff for nutrient analyses might have had some increased nitrogen concentrations. The presence of $NO_3^-$-N concentrations in 4$^{th}$ June 2006 event indicated that there was some effect of fertiliser that could not be fully quantified due to the very small event on 27$^{th}$ May 2006.

The spring N fertiliser (urea) application (N = 40 kg $ha^{-1}$) had a large effect on TN concentrations in runoff on 17th November 2006. The TN concentrations and total losses were increased greatly in both treatments. Although differences in concentrations were not significant between treatments the total $NH_4^+$-N and TN losses were substantially higher from OP than TP. Smith & Monaghan (2003) have shown that losses of N in overland flow from pastoral land were the greatest in soils receiving 400 kg N $ha^{-1}$ $yr^{-1}$ in Southland, New Zealand. Similarly, Sharpley & Syers, (1979) reported that a late June (winter) application of Urea (N = 60 Kg $ha^{-1}$) resulted in a total drainage loss of 3.14 kg N $ha^{-1}$ in a four week period suggesting that most of the losses were probably in surface runoff water. The lower N losses following urea application in TP than OP were probably due to smaller runoff volume from TP. Fu et al., (2004) reported that an agroforestry system involving poplar trees limited the runoff, soil and nitrogen losses compared with farmland in China.

### 5.4.5 Nutrient losses in drainage water

DRP concentrations in soil extracted solution using suction cups generally remained very low compared with runoff concentrations. However, the post-fertiliser autumn event had increased DRP concentrations of environmental concern from OP and TP (0.97 ± 0.34 mg $L^{-1}$ vs 1.31 ± 0.632 mg $L^{-1}$, respectively). Similarly, the post-winter grazing event maintained a considerably high level of DRP concentrations. Studies involving dairy cattle have shown that P concentrations increased considerably as a result of grazing. For example, Sharpley & Syers (1979) reported peak dissolved inorganic phosphorus (DIP) concentration of 0.25 mg $L^{-1}$ as a result of grazing. However, Houlbrooke et al., (2003) reported peak DIP concentration of 0.15 mg $L^{-1}$ which was considerably lower than those reported by Sharpley & Syers (1979). These differences were attributed to the livestock density suggesting that the negative impact of grazing can be reduced by managing livestock on pastoral lands.

Since the inception (Briggs & McCall, 1904) and experimental testing (Krone et al., 1951) of porous cups, nutrient transport in water draining through the soil profile has been widely monitored by extraction of soil water using this method (McGuire & Lowery, 1994; Williams & Lord, 1997). However, there is wide discussion in the literature on the sorption tendencies of suction cups for organic and inorganic compounds (Hansen & Harris, 1975; McGuire et al., 1992; Wagner, 1962). Nagpal (1982) evaluated ceramic porous cup samplers and reported that during the rest period when samplers remained in contact with solution at zero tension, the P sorption capacity of the ceramic cup was enhanced. Similarly, porous cups subjected to high P solution concentration initially, released phosphorus when flushed with a solution of low concentration. Severson & Grigal (1976) indicated that length of extraction time may affect the concentration. Their report showed that as the extraction time increased, the extracted sample more closely represented the soil solution. Zimmermann et al., (1978) reported only 43 ± 1.1 % recovery of P after solution was filtered through ceramic cup samplers compared with the original solution concentration. Nevertheless, despite inconclusive discussion on the nature and effectiveness of the suction cup method, the results from the current experiment could still be valid to describe the differences between treatments (OP vs TP) irrespective of the difference between actual concentration in the soil solution and the one measured after filtration through ceramic cups.

The lack of any detectable $NH_4^+$-N and $NO_3^-$-N concentrations (<0.25 mg $L^{-1}$) in post grazing events suggest that sheep urine did not pass beyond 300 mm depth. This supports earlier findings by Sakadevan et al., (1993) when application of sheep urine to the surface did not pass beyond the 250 mm soil depth. However, results are not in agreement with findings by Houlbrooke et al., (2003) from the same soil type at a nearby site under dairy grazing management. The authors reported an increase in $NO_3^-$-N concentration of 5 mg $L^{-1}$ in drainage water as a result of grazing. The elevated $NO_3^-$-N concentration (10 mg $L^{-1}$) reported by Sharpley & Syers (1979) following grazing by dairy cattle at a stocking rate of 300 cows $ha^{-1}$ suggested that the amount of excreta and livestock grazing density affected the $NO_3^-$-N concentration in drainage water. This was probably true in the current study because sheep excreta cannot match the quantity of cow excreta. However, greater losses of $NO_3^-$-N in the above studies have been attributed in part to the preferential movement of urine by macropore flow down cracks and channels to mole drains. Silva et al., (2000) conducted a field lysimeter experiment to determine the effect of macropore flow on the transport of cow urine N through soil and reported that pores >600 μm transmitted about 98 % of the total N leached below 700 mm depth.

# 5.6 Conclusions

## 5.5.1 Moginie experiment

The decrease in soil moisture content by willow and poplar was greatest in the upper 0-150 mm soil depth and was mainly restricted to summer and autumn months. However, there was a trend of smaller soil moisture content in deeper layers in TP than OP. The repeated measures analyses revealed that soil moisture was significantly lower in TP than OP in all the monitored soil depths (i.e. 0-150, 0-300 and 0-450 mm). It is suggested that willow have shallower roots than poplar, therefore, they probably absorbed soil moisture from different depths.

The effect of trees on surface runoff increased over time. Although cumulative surface runoff was higher ($P = 0.0832$) from OP than TP, seasonal results showed that trees were more effective in spring 2006 than spring 2005, suggesting that willow and poplar can significantly reduce the quantity of surface surface runoff at the age of four years if planted at high density (>6000 stems $ha^{-1}$). However, the deciduous nature of willow and poplar makes them ineffective in winter and early spring in reducing surface runoff.

Soil loss in surface runoff was significantly ($P = 0.0158$) greater from open-pasture than tree-pasture ($443 \pm 67.2$ kg $ha^{-1}$ vs $212 \pm 27.9$ kg $ha^{-1}$, respectively). The major sediment load transported through runoff was in the form of ISS (73.5 %) followed by OSS (26.5 %) in both treatments. Winter grazing caused greater soil disturbance from OP than TP which led to significantly greater soil loss in runoff from OP than TP. TSS losses were highest in winter 2006 from OP (73 %) and TP (63.6 %) than other seasons. Spring 2005 losses were 21 % and 26 % while the spring 2006 contribution was the least (1.6 % vs 2.8 %) from OP and TP, respectively. Although autumn contribution was 4 % and 7.5 % from OP and TP the major share was from simulated rainfall events.

Overall, trees were not effective in reducing total P losses, partly due to greater deposition of dung in tree plots as a result of preferred sheep camping.

Therefore, the cumulative total P losses were similar (23 kg ha$^{-1}$), for OP and TP with the largest contribution from spring 2006 (56.5 %) followed by winter (35 %). Autumn losses (6.5 %) were dominated by simulated rainfall events, but spring 2005 losses were nominal (2 %) in both treatments.

The dilution effect under willow and poplar was significant due to reduced runoff from tree-pasture than in treeless pasture. Therefore, the cumulative DRP losses were significantly higher ($P < 0.05$) from OP than TP (6.22 ± 0.25 kg ha$^{-1}$ vs 2.95 ± 0.74 kg ha$^{-1}$) and accounted for 21 % and 17 % of total P, respectively. Spring 2006 losses (45 % vs 34 %) were significantly higher ($P$ = 0.0469) from OP than TP while winter losses were similar (35 %). The autumn 2006 losses were four times higher than spring 2005 for pasture with and without trees.

Winter grazing effect on total P and DRP losses was greater than spring grazing. Similarly, autumn and spring P fertiliser application significantly increased total P and DRP concentrations in both treatments. Pre-fertilisation soil water status significantly affected the P losses in surface runoff.

Trees had a significant effect on TN losses in surface runoff. The cumulative TN losses over the study period were 15.2 ± 0.35 kg ha$^{-1}$ and 7.2 ± 1.54 kg ha$^{-1}$ from OP and TP ($P$ = 0.0267), respectively. The major contribution was from post-grazing and post-urea events. Winter contributed the highest losses (57 %). However, spring 2006 contributed the second highest losses and losses were significantly higher from OP than TP (35 % vs 24 %, respectively). The spring 2005 (7.5 %) and autumn 2006 (6.5 %) losses were statistically similar between treatments. $NO_3^-$-N contribution in TN was also similar between treatments (3 %). Similarly, the ammonical nitrogen was also similar between treatments and its contribution to TN was 18.5 %.

The $NH_4^+$-N and $NO_3^-$-N concentrations in drainage water remained below detectable level in all the post grazing events. However, urea application in spring increased the $NH_4^+$-N concentration in both OP and TP treatments. The DRP concentrations in drainage water were increased by post-grazing and P fertiliser events. However, concentrations were lower than DRP concentrations in surface runoff water and remained statistically similar between treatments.

### 5.5.2 Riverside experiment

The cumulative surface runoff at Riverside Farm was similar (P = 0.8443) between OP and WP (30 mm). However, in summer, WP did not yield any runoff suggesting that willow along with un-grazed grass were effective in reducing the quantity of surface runoff.

The cumulative TSS losses were similar (P = 0.6175) between OP and WP (15 kg ha$^{-1}$). The cumulative ISS losses were also similar (P = 0.1863) between OP and WP (11 kg ha$^{-1}$) while OSS contribution (P = 0.8425) was only 4 kg ha$^{-1}$.

The cumulative total P losses were similar between OP and WP (0.18 kg ha$^{-1}$). Similarly, cumulative DRP losses were also statistically similar (P = 0.8075) between OP and WP (0.036 kg ha$^{-1}$) contributing 13 % and 37 % of total P losses from OP and WP, respectively. The cumulative TN losses in runoff over the study period were similar (P = 0.7532) between OP and WP (1.1 kg ha$^{-1}$).

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# GENERAL DISCUSSION AND CONCLUSIONS

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## 6.1 Introduction

Silvopastoralism aims at the conservation and utilization of the farm's natural resources on a sustainable basis. Many of the current farming practices employed in hill country in New Zealand are not environment friendly (Houlbrooke et al., 2003; Quinn & Stroud, 2002) and need to be improved. The multipurpose attributes of willow and poplar make them potentially useful for silvopastoral systems, especially in hill country, where soil erosion is widespread, and summer and autumn drought results in low pasture production. Despite some studies regarding the effects of willow and poplar on pasture growth (Douglas et al., 2001; Guevara-Escobar, 1999) and forage production (Oppong et al., 2001), little research has been undertaken to understand their effects on runoff, soil erosion and nutrient losses. It is also important to quantify their effect on pasture growth when planted at high density. Therefore, a series of field trials were conducted to compare the impacts of willow- and poplar pasture systems with traditional open pasture. The influence of densely planted young willow and poplar on pasture production, soil water status, runoff, soil erosion and nutrient loss were discussed in Chapters Three through Five. The current Chapter aims at a general discussion of the findings in order to provide useful insights into the future improvement of silvopastoral systems in New Zealand.

## 6.2 Effect of trees on soil moisture content

The effects of densely planted young willow and poplar trees (<5 yrs) on soil moisture content were investigated in three different field trials. Tree age, size and management had considerable effects on soil moisture status. The results showed that coppiced willow trees (Chapter 4) with late spring browsing did not affect soil moisture in the following summer and autumn. This was partly due to the reduction in the number of leaves on the trees which reduced the photosynthetic activity and transpiration. Similarly, newly established willow and poplar trees (Chapter 3) had no significant effects on soil moisture content in the first year of growth when compared with open pasture. The plant competition for moisture within the topsoil during tree establishment is considered to be intense due to the dense fibrous root system of grasses and there have been reports of reduced establishment and subsequent growth of young conifers due to competition with grasses (Eissentat & Mitchell, 1983) especially at dry sites (Cole & Newton, 1986). Similarly, McPherson (1993) reported 85 % reduction in root biomass of *Quercus emoryi* seedlings due to interference from native grasses, suggesting that grasses competed for soil water and nutrients. Therefore, it is recommended that any vegetation that is likely to compete with newly established trees be suppressed for one to two years after tree planting in silvopastoral systems (Sharrow & Fletcher, 1995).

In the second year of their growth (chapter 3), densely planted willow and poplar started influencing soil moisture, especially in the top 0-300 mm soil depth in summer and autumn, suggesting that tree roots extended beyond pasture roots. However, despite being the same age, willow trees were more effective than poplar due to their greater size (height, stem diameter and number of shoots). According to Sharrow (1999), trees start exerting greater influence on the soil moisture content when tree roots extend beneath the pasture root zone and pasture loses its influence on newly establishing trees.

Even greater effects on soil moisture content were observed with willow and poplar trees of three to four years of age (Chapter 5). Although the effect of this age group of trees was greater in the top 0-150 mm soil depth, a trend of smaller soil moisture content was also observed in the deeper soil strata. The stable coexistence of grasses and trees in a silvopasture depends on both species being able to access soil resources. There is a general understanding that the effect of trees on soil moisture content is positively correlated to their age and size. Also, trees utilise soil water from deeper layers than grasses and the depth increases with age of the tree. Jake & Guy (1997) tested this concept on different aged *Quercus emoryi* trees in temperate savana, Arizona, USA. Their results showed that tree seedlings utilized shallow sources of soil water (<15 cm), while 1-2 year old saplings utilized water to a depth of 20-35 cm and mature trees used deeper sources of water (<50 cm). These authors also noted that trees switched from shallow to deep water sources within one year of germination. This American work supports the findings in the current study.

The decrease in soil moisture content by trees was mainly restricted to summer and autumn. Sharrow (1995) also reported that competition for soil water between trees and understorey pasture is usually greatest in the summer. However, measurements under 4 year old willow and poplar trees (chapter 5) also showed decrease in soil moisture in spring, suggesting that the effect of trees on soil moisture was greater with age. Being deciduous trees, willow and poplar have the inherent disadvantage of losing all their leaves between late autumn and early winter, under New Zealand conditions. This defoliation decreases their capability to influence soil moisture in winter and early spring. Although, willow and poplar grow and develop new leaves every year in spring this can be later than the period of maximum soil moisture in early spring.

## 6.3 Pasture production under trees

The effects of densely planted young willow and poplar on understorey pasture production were measured in two field trials (Chapters 3 and 4). Results from these trials showed that shade was the major factor limiting pasture growth under trees. Relative to growth in open pasture, willow and poplar reduced pasture growth by 22 % and 9 % in their 2$^{nd}$ year, respectively. The pasture production under coppiced willow reduced by 48 % compared with open pasture (Chapter 4) and this decrease was attributed to tree shade and pasture species composition differences. The lower soil moisture content under trees (Chapter 3), especially in summer and autumn, also had some negative impact on understorey pasture growth.

Shade has been shown to make a major contribution to the reduction in pasture growth under trees. For example, Guevara-Escobar et al., (2007) reported a 40 % reduction under mature poplar trees that was attributed to shade. Similarly, Wall (2006) estimated a reduction in understorey pasture production of 6.6 % for every increase in canopy closure ratio of 10 % from a poplar stand. Shade can alter the pasture species composition under trees compared with open pasture (Burner & Brauer, 2003). Under trees, the most productive species in spring like ryegrass are discriminated against thereby affecting the overall understorey pasture growth. Nevertheless the negative impact of trees in plantations such as willow browse blocks can partly be offset through management practices like sheep browsing at intervals that favour pasture production. However, it is important to realise that frequent sheep browsing will have a negative bearing on the ability of young trees to dry out wet areas.

The current results highlight the importance of grazing for the yield and quality of understorey pasture. The understorey pasture quality deteriorated when browsing was delayed for long periods (Chapter 4). Johnson et al., (1986) reported that the clover content of pastures tends to decline with increasing tree canopy. Guevara-Escobar et al., (2007) reported 8.9 % lower digestibility and 1.5 MJ $kg^{-1}$ lower metabolisable energy of pasture DM under the poplar canopy than in the open pasture.

Like all other agricultural systems, the productive capability of the tree and pasture components in silvopastoralism depend on the exploitation of solar energy through photosynthesis. The understorey pasture growth is dependent on the size and efficiency of its photosynthetic activity. Since light quantity and quality is altered when it passes through the overstorey tree canopy, the understorey pasture photosynthesis is affected by the canopy size, especially at the maximum leaf area. As a general rule, the tree root density and canopy effects are greatest close to the tree stem and decrease with distance from the tree stem (Sharrow, 1999). Coppicing of willow trees results in a greater number of shoots, thereby giving a more branched tree (Oppong, 1998). Most herbaceous plants reach leaf compensation point for photosynthesis at approximately 10% of full sunlight (Gardner et al., 1985) and coppice trees can reduce light close to the compensation point, especially close to the stem, as seen in the current study at the Riverside site. Hart et al., (1970) reported 7 % of incident radiation under *Pinus illiottii* trees. However, low light under trees may be some what compensated for by cooler temperatures in the shade, which increases the efficiency of light use by plants (Brown, 1982) during warm days. Nevertheless, even fertiliser application may not increase pasture production at the compensation point (Braziotis & Papanastasis, 1995).

The influence of trees on understorey pasture production increases with tree age/size when competition exceeds facilitation (Sharrow, 1995). Stand level investigations on conifer tree/understorey pasture relationship have shown a general reduction of forage production with increasing tree basal area or canopy (Joyce & Mitchell, 1989; Tapia et al., 1990; Wall, 2006). A similar trend of reduced understorey pasture and livestock production with increasing tree leaf area due to changes in tree density and growth have been reported from silvopasture systems by; (Hawke, 1991; Johnson et al., 1986; Knowles, 1991).

Past studies have indicated that the reduction in tree leaf area can be helpful to improve understorey pasture growth. This can be achieved through silvicultural practices such as tree thinning and pruning. However, this does not seem practicable in willow browse blocks because the trees are maintained at a constant density (>6000 stems $ha^{-1}$). However, using sheep browsing to reduce leaf area is an effective tool to offset the adverse effect of shade on pasture growth. Also, the continuous practice of coppicing of willows every year helps control tree height and LAI to minimise the compounding of deleterious effects of shading as seen in many block plantations.

## 6.4 Surface runoff, soil erosion and nutrient loss

As a result of rainfall, pastoral land is subjected to runoff leading to accelerated soil erosion. The degree of runoff depends on, amongst others, factors like rainfall intensity, slope of the land and soil type. These factors are not changeable on a large scale by human interference. However, certain practices can help modify the impacts of runoff. These practices include biological (tree planting) and engineering measures (e.g. construction of field terraces, check dams, wire crates and dykes). As the vegetation mix is different in silvopastoral systems, they may have a beneficial effect on runoff.

As willow and poplar are leafless in winter and early spring, they will not ameliorate runoff generation to any extent at this time compared with open pasture. Large Olsen P values in the topsoil (0-2.5 cm) will have serious implications for P losses (Aye et al., 2006) in runoff particulally if the soil is unprotected. However, these trees can be very effective from spring onward depending on their size. The results from the Moginie experiment (Chapter 5) showed that willow and poplar trees had a greater effect on runoff in spring

2006 than spring 2005. Also, the management practices such as coppicing affected the influence of willow trees on runoff and sediment load.

In the current study, vegetative cover using densely planted willow and poplar trees reduced sediment load suggesting that soil erosion can be minimised through a silvopastoral system. Sheep grazing, especially in winter, increased sediment transport in OP by four fold compared to TP in the immediate post-grazing runoff event. These differences were attributed to lesser soil disturbance and increased infiltration rates in tree pasture than open pasture. The modelling work on catchment sediment losses from land under deer farming by Thorrold & Trolove (1996) found 4.5 times greater losses than from forestry. Other studies have also reported increased soil erosion due to livestock treading (Evans, 1996; McDowell et al., 2004). Similarly, Carroll et al., (2004a) reported that water infiltration rates in areas with young trees were up to 60 times greater than adjacent pasture.

Nutrient losses (N and P) are also linked to runoff and sediment load and any activity that causes reduction in both these is likely to offset nutrient losses from pastoral lands. However, soil loss alone does not explain the actual nutrient enrichment of surface runoff water from pastoral lands. Dissolved P associated with livestock excreta (urine and dung), applications of N and P fertilisers and desorption reactions with the soil is the other major form of nutrient enrichment of fresh water bodies. In the current study, all these possible sources of nutrient contribution from farmland were studied and results have shown that livestock grazing and fertiliser applications increased N and P concentrations above minimum threshold levels required to cause eutrophication of freshwater rivers and streams (Australia and New Zealand Environment and Conservation Council, 2000) and posed serious risks to aquatic fauna. However, $NO_3^-$-N concentrations were within the limits for drinking water (Ministry of Health, 1995) in surface runoff and drainage.

In the current study the N and P concentrations in the runoff water from areas under willow or poplar were similar to/or even greater than those in the runoff from the open pasture area. In part, this may well have been due to greater return of excreta to the areas under the trees due to the preference of grazing sheep to camp and shelter under the trees rather than on open pasture. However, losses (kg $ha^{-1}$) of total P in runoff from the two areas were not significantly different. In contrast, TN and DRP losses (kg $ha^{-1}$) were significantly lower in tree-pasture than open pasture at Moginie. Since dissolved forms of P are readily available for uptake by aquatic flora (McDowell & Koopmans, 2006), reduced DRP losses under a silvopastoral system can help reduce eutrophic effects.

Livestock grazing can increase the quantities of sediment and nutrient losses from pastoral lands. In the current study, the sheep grazing had a marked influence on sediment and nutrients losses. Winter grazing clearly showed detrimental effects. New Zealand receives most rainfall in winter and early spring. During this period, the soil is often very wet. Also, pasture growth is at its minimum (Chapters 3, 4). Livestock grazing during this time of the year resulted in large amounts of soil disturbance and very poor pasture growth was not helpful in providing immediate soil cover and protection. Therefore, increased rainfall caused greater soil erosion, and runoff water carried higher levels of nutrients from urine and dung.

Although the greater soil moisture deficit that is carried over from summer and autumn under trees may help reduce runoff, as willow and poplar are deciduous they can not mitigate the direct impact of rainfall in winter. However, tree roots can still provide reinforcement for soil stability to reduce major slips and slides (Ekanayake et al., 2004; Hawley & Dymond, 1988; O'Loughlin, 2004). The results from the current study also suggest that soil disturbance due to sheep grazing could be lesser in a silvopasture compared with open pasture area because higher infiltration rate (Carroll et al., 2004b; Joslin & Schoenholtz, 1997) in tree pasture may help topsoil dry out quickly leading to less compaction and soil disturbance. However, at times, soil compaction could be greater close to the tree stem due to preferred camping by the sheep but it should ease with distance from the main stem (Wairiu et al., 1993) due to the support afforded to the soil by the tree root system.

The present study also identified sheep camping behaviour and some of its implications. Sheep preferred to camp under trees in all seasons except during day-time in winter when they utilized open pasture. Therefore, increased dung and urine deposition was more likely under trees than open pasture. The deciduous nature of willow and poplar helps discourage the preferred camping behaviour of the sheep for a few months of the year. If there was a mix of tree and open pastures in the same paddock then evergreen trees may encourage greater camping and excreta return under trees. However, a block plantation on a farm with full livestock access could potentially become a point source for nutrient losses. The results from this study support the existing trend of planting willow and poplar trees at wide-spacing for better distribution of dung and urine on a farm. The results also suggest that livestock access to riparian strips should be limited because of their close proximity to rivers and streams.

## 6.5 Constraints faced during the study

Measurement of surface runoff in field trials requires substantial physical and financial input. The number of replicates at the experimental sites was limited by the funding available. Ideally, there would be four or more replicates of the runoff plots. Financial resources also hindered the frequency of data measurement:, measurement of the soil moisture content at Riverside Farm was especially constrained by the cost of the travel involved.

The Riverside site did not prove appropriate for runoff measurements in winter. The willow block was located at the bottom of a hill. At the start of the experiment, (spring) runoff was quite stable and it did not signal any disparity between the willow area and the pasture area and data collection continued as normal. However, at the start of winter 2006 the runoff in willow plots had additional water input from the area behind the plots. Therefore, this data was very difficult to interpret. This resulted in the cessation of further measurements. However, measurements at the open pasture site were quite normal.

Excess soil moisture, especially at the bottom of foothills can also be a disadvantage to pasture production (in willow blocks such as in the current study at Riverside Farm (Chapter 4). Such sites are usually poorly productive due to the long-term adverse environment that existed prior to tree planting.

Lack of data on pasture growth in the pre-tree period made it difficult to evaluate the positive role of willow to rehabilitate these sites in a post-tree environment.

## 6.6 Future research needs

It is suggested that future studies to extend the research described in this thesis should focus on the following.

### 6.6.1 Willow and poplar root extension and distribution

The results for soil moisture content in the current study have indicated that willow and poplar rooting systems extend to different soil depths. There has been some effort to explore the poplar rooting system in recent years in New Zealand (McIvor et al., 2006) but trees younger than five years have not been studied. Also, knowledge on willow root distribution is lacking in New Zealand. If it is shown that willow and poplar rooting systems extend to different depths, both species could be integrated into silvopastoral systems to provide the additional benefit of creating moisture deficits at greater soil depths, thereby reducing the quantity of surface runoff. Also, tree survival under higher browsing frequency should be included as part of such a study.

### 6.6.2 Sheep browsing as a tool to improve understorey pasture growth

In the current study, early November sheep browsing significantly reduced willow leaf area compared with the non-browsed trees. Literature suggests that reduction in overstorey tree leaf area may increase the understorey pasture growth. Its quantification in willow browse blocks is important to offset the negative impact of tree shade on understorey pasture. This will also help identify the optimum browsing frequency and timing. However, such a study should include the effect of browsing episodes on soil moisture content to find a balance where trees can still create significant moisture deficits without unduly limiting understorey pasture growth.

### 6.6.3 Integration of evergreen tree species

The deciduous nature of willow and poplar exposes the topsoil to the direct impact of rainfall in winter and early spring. Although major slips and slides may not occur due to reinforcement of soil with roots, runoff and sheet erosion might continue at the same scale as in open pasture. Therefore, the possibility of integrating an evergreen or semi-evergreen tree species seems worthy of investigation. However, the spacing and proportion of such species needs careful study so that the understorey pasture growth is not compromised and/or the preference of animals to camp under trees does not lead to the depositing of large amounts of excreta under trees.

### 6.6.4 Willow gall sawfly effect on tree leaf area development and sheep health

During the course of this study it was observed that willow gall sawfly appears on most of the leaves and remains until the leaves fall. It was observed that sawfly affected the leaf growth thereby reducing the leaf area. Sheep eat sawfly during browsing. Its implications to sheep health are also not known. Therefore, it is suggested that future research could look for methods to eradicate sawflies so that willow fodder could be free of such an unwanted parasite.

## 6.7 Conclusions

The current study highlighted the importance of trees on pastoral lands. The densely planted young willow and poplar (3-4 yrs) reduced sediment load by 52 %, and decreased total nitrogen and dissolved reactive phosphorus by 47 % each in surface runoff compared with open pasture. Trees also decreased runoff and soil moisture as they aged. Willow grew faster than poplar and reduced pasture growth by 23 % and 9 % in their second year, respectively. Sheep grazing, especially in winter, increased sediment and nutrients load in runoff water and had environmentally deleterious effects on water quality. Similarly, fertiliser application increased the nutrient concentrations well above the threshold level to alarm eutrophication of freshwaters in New Zealand.

Willow and poplar decreased the surface runoff compared with open pasture treatment and the indications are that their influence will be greater with tree age and size. However, their deciduous nature and coppicing made them ineffective to reduce the surface runoff in winter and early spring. Therefore, deciduous tree-based pastoral system requires sufficient grass cover in winter to minimise the rain impact.

Sediment load was significantly reduced in the tree pasture system compared with open pasture over the study period. Sheep grazing in winter resulted in greater soil disturbance and erosion in open pasture than tree-pasture. Therefore, it is concluded that increased moisture deficit and infiltration under trees reduced the hooves impact in terms of soil compaction and disturbance. Coppiced willow did not reduce soil erosion until their trees regained full canopy.

Nutrient concentrations in surface runoff were generally similar in both treatments despite greater deposition of dung and urine under trees due to preferred sheep camping. However, reduced runoff in tree-pasture offered lesser dilution. Therefore, dissolved reactive phosphorus losses were greatly reduced under tree pasture and reduced the potential for eutrophication of freshwaters as dissolved forms of phosphorus are readily available for plant uptake such as algae. The total nitrogen losses were significantly lower in tree-pasture. The ammonical and nitrate nitrogen concentrations were not detectable for all the runoff and drainage events. However, detectable concentrations and cumulative losses were similar in tree-pasture and open pasture. The dung and urine deposition from sheep grazing and N and P fertiliser application significantly increased nutrient concentrations and total losses.

The effect of densely planted willow and poplar in decreasing soil moisture was greater in summer and autumn months compared with open pasture. However, willow and poplar had no influence on soil moisture in their first year, but their effect increased in the subsequent years. Trees influenced soil moisture more in the top 0-150 mm soil stratum than deeper soil strata, but the decrease in the deeper soil strata increased with age and tree size.

The understorey pasture growth was affected by willow and poplar overstorey compared with open pasture area. Tree shade was the dominant factor influencing the pasture growth, although summer and autumn pasture growth was also affected by reduced soil moisture. Management of the trees canopies through browsing or coppicing is necessary to maintain pasture production in browse blocks.

The current study advances our environmental understanding of the tree pasture system. The study included a number of aspects which, in the past, were not reported or were reported in isolation. The key findings were reduced soil moisture, runoff, sediment and nutrient losses in a willow-poplar pasture system compared with open pasture. The current research work provided sufficient insight to point out definite areas that require multidisciplinary research in future. Information from this study and the reviewed literature support the value of willow- and poplar pasture system in reducing runoff, soil erosion and nutrient losses from New Zealand pastures.

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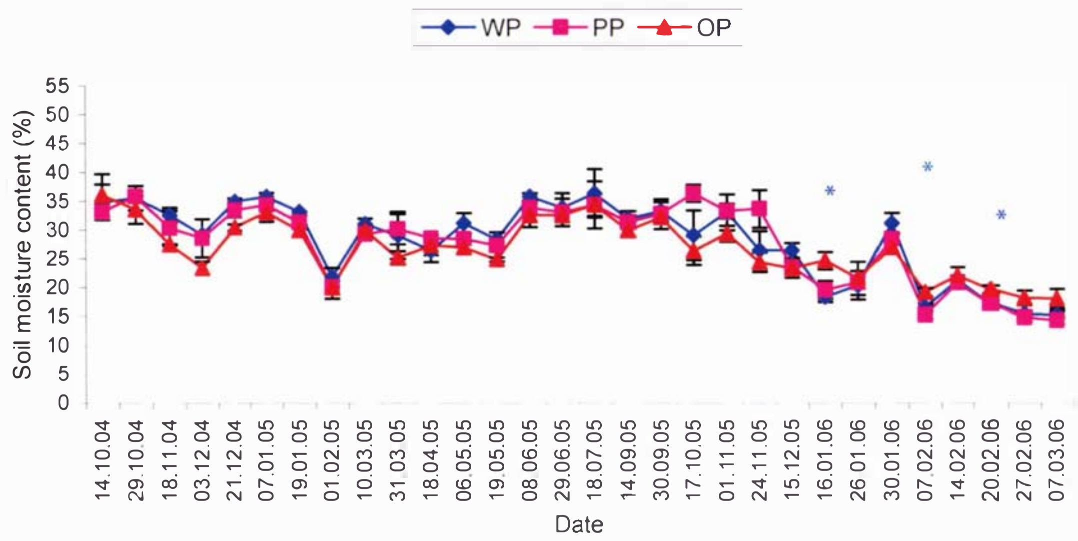
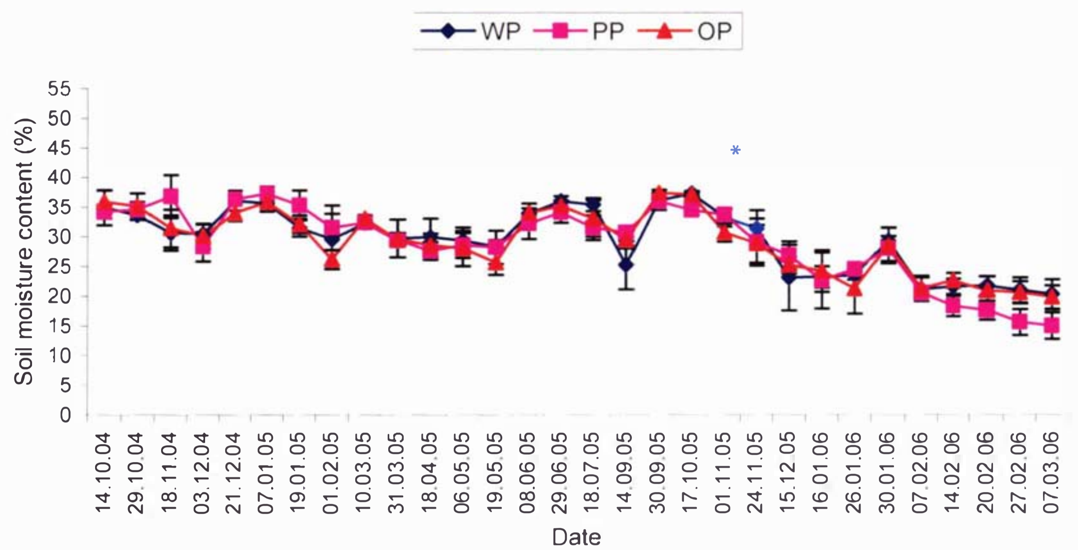
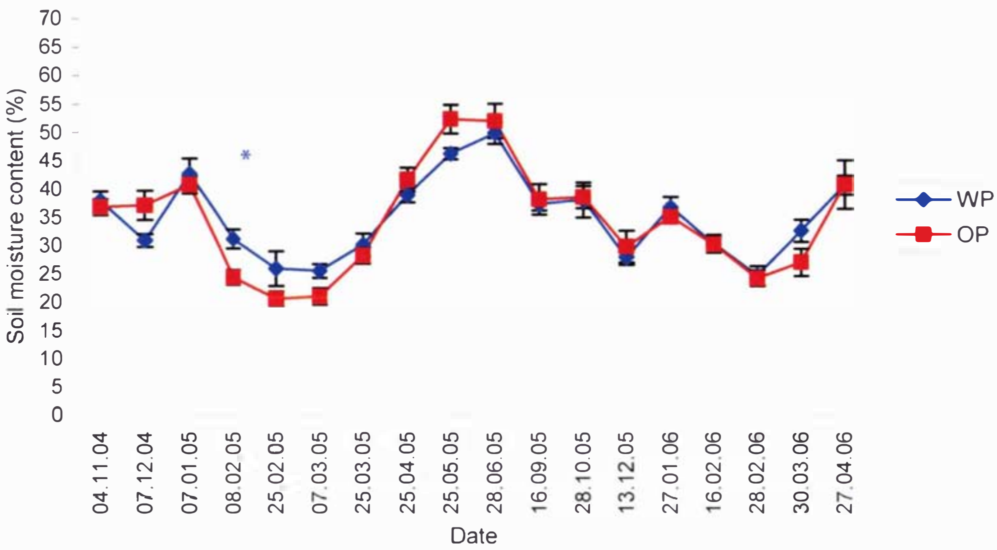
# Appendices



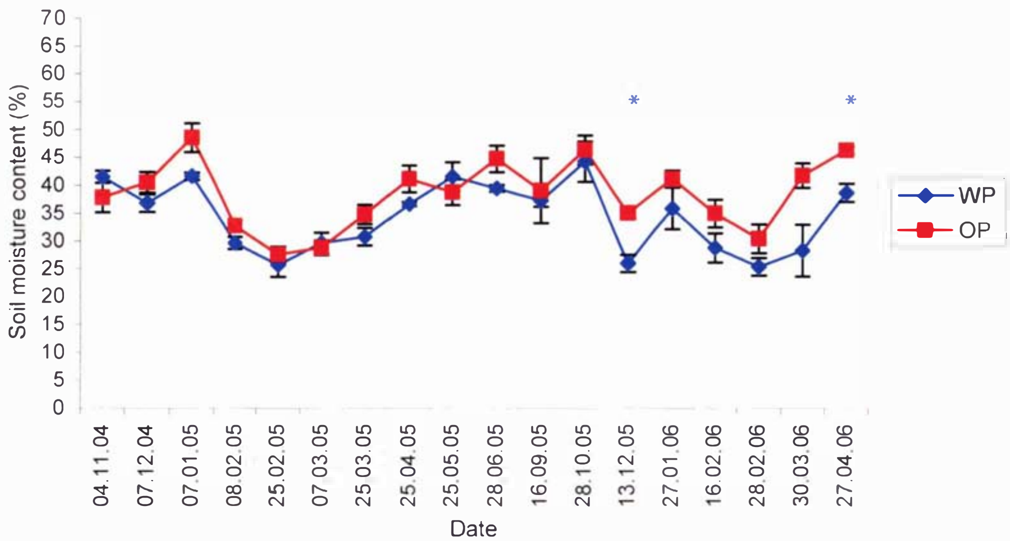

Appendix 3.1 Volumetric soil moisture content (%) at 150-300 mm depth in willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at Moginie Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.



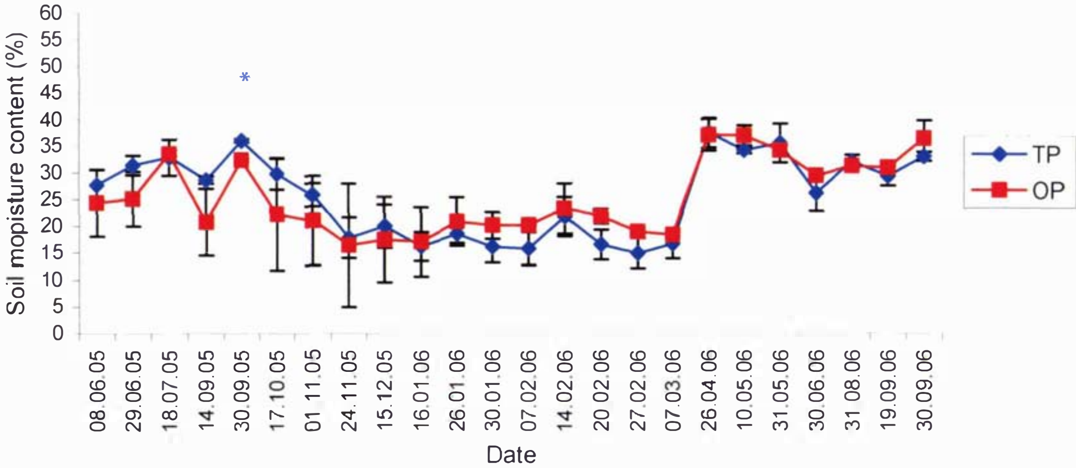

Appendix 3.2 Volumetric soil moisture content (%) at 300-450 mm depth in willow pasture (WP), poplar pasture (PP) and open pasture (OP) treatments at moginie Line bars show the SEM for each treatment. * denotes significance at P < 0.05.



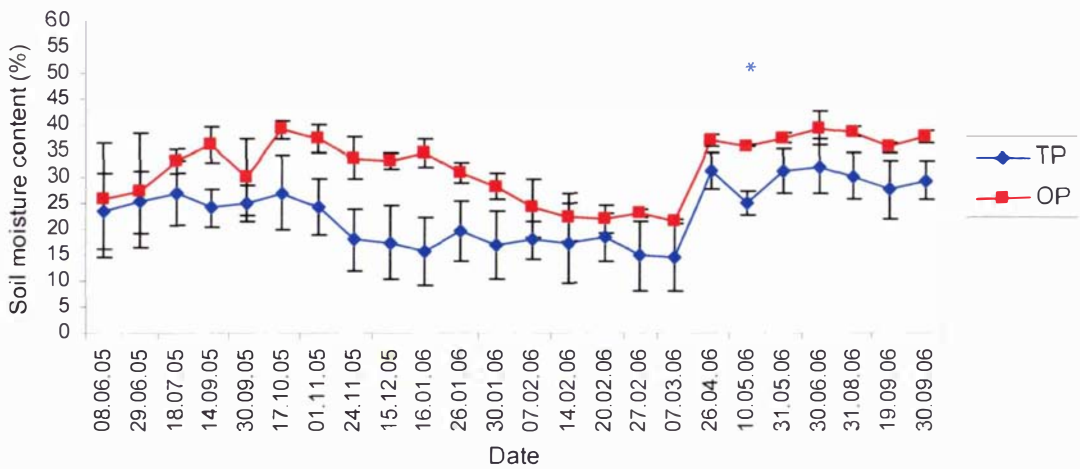

Appendix 4.1 Volumetric soil moisture content (%) at 150-300 mm depth in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm. Line bars show the SEM for each date. * denotes significance at $P < 0.05$.




Appendix 4.2 Volumetric soil moisture content (%) at 300-450 mm depth in willow pasture (WP) and open pasture (OP) treatments at Riverside Farm. Line bars show the SEM for each date. * denotes significance at $P < 0.05$.




Appendix 5.1 Volumetric soil moisture content (%) at 150-300 mm depth in open pasture (OP) and tree pasture (TP) treatments at moginie, manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.




Appendix 5.2 Volumetric soil moisture content (%) at 300-450 mm depth in open pasture (OP) and tree pasture (TP) treatments at Moginie, Manawatu. Line bars show the SEM for each treatment. * denotes significance at P < 0.05.