ESTABLISHMENT AND SILVOPASTORAL ASPECTS OF WILLOW AND POPLAR

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Abstract

Willow and poplar are the main trees used for soil erosion control in New Zealand (NZ) with successful establishment critical to greater use of this technology. Five experiments were conducted at the Pasture and Crop Research Unit, Massey University Palmerston North, NZ to examine the ability of willow and poplar to establish as a willow/poplar pasture system in NZ over a period of 3 years from December 2002 to April 2005. With an objective to select the best size for low cost planting, stem diameters (10 mm, 25 mm and 35 mm) were planted vertically and stem lengths (50 mm, 200 mm and 600 mm) were planted horizontally to determine their growth, establishment, biomass production and regrowth after browsing. From December 2002 to March 2003, three management treatments, mowing, herbicide and control (no weed control) treatments, were designed and applied to determine their effects on growth and shoot biomass production. From September 2004 to April 2005, mowing was replaced by sheep browsing and the effect of browsing, herbicide and control treatments on soil and tree water status (soil water content, soil water loss and deficit, and stem water potential) were examined. Longer (600 mm) and thicker stem diameters (35 mm) produced the greatest shoot biomass (edible biomass, total biomass and root biomass) compared to the thin stem cuttings (50 mm length and 10 mm diameter). Higher tree survival was also found for longer (600 mm) and thicker stems diameter (35 mm). The mown treatment produced significantly more edible and total shoot dry matter (DM) than the herbicide and control treatments, with willow clone 'Kinuyanagi' producing higher total shoot DM than 'Tangoio'. Pasture management had no significant effect on soil water content during spring 2004 and late summer/autumn 2005, however, it was significant during early and mid summer. Strong relationships between (i) soil water content and stem water potential (SWP), and (ii) SWP and soil water deficit were found and could help growers to predict the amount of water required during the growing season. The results clearly demonstrated that sheep grazing had negligible damaging effect on willow and poplar (main stem, branch breakage and tree leaning) and tree mortality, and that young trees can be browsed during pasture shortages in summer drought. Cutting size and

understorey control for establishing willow and poplar into pasture have been better defined by this research. It is recommended that farmers establishing willow and poplar for fodder plant thick (vertical planting) and long stems (horizontal planting) for higher growth and biomass production.

Keywords: willow; poplar; stem diameter; stem length; planting depth; understorey management; fodder biomass; soil water; sheep grazing.

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1 GENERAL INTRODUCTION

CONTENT

1.1 Introduction and objectives

Lack of pasture production during dry summers is a problem faced by many New Zealand farmers. Planting of willow and poplar is one option to provide fodder supplementation to assist with meeting feed demands during summer/autumn drought. In New Zealand willow and poplar browse blocks are established for reclamation and production of edible biomass during dry periods, particularly using wetter sites with low pasture production (Charlton *et al.* 2003). Browse blocks based on willows are a relatively new use of willows in New Zealand recently popularised by Douglas *et al.* (2003). The high plant population density (5000- 8000 stems/ha) used in browse blocks means there is farmer interest in a cheap, fast and effective method to established the trees.

A major advantage of willows and poplars over other temperate shrubs and trees used for browse is that they can establish from stem cuttings. The stem cuttings need to be able to establish in competition with pasture and in environments where dry summers are prevalent and the young trees are browsed by livestock. Kemp *et al.* (2003) showed that willow and poplar have several other advantages over other browse species. They are used widely in New Zealand for soil erosion control (Cameron 2003), and the leaves of these trees have a nutritive value which is similar to normal summer pasture, or greater than for summer drought pasture (McCabe & Barry 1988; Kemp *et al.* 2001; Kemp *et al.* 2003). Fast growth and an ability to coppice and root from stem cuttings (Fung 2001) make willow and poplar easy to grow and suitable for supplying supplementary fodder during summer/autumn drought (Douglas *et al.* 1996; Douglas *et al.* 2003).

Willow and poplar can be established by using stem cuttings (Zsuffa 1992; Douglas *et al.* 2003) planted either vertically or horizontally. Horizontal planting is a pioneering project reported in this thesis. The idea was taken from farmers' experience in observing the growth of shoots from willow stems naturally lying on the ground producing shoots and roots unaided (Ms. Sian Cass personal communication, 2 August 2006). However, the size of stem cuttings is important in determining the extent of successful establishment, growth and biomass production, and ultimately establishment cost. It is hypothesized that

thick and long stem cuttings have more potential growing points and greater nutrient reserves which will lead to higher shoot growth and biomass production. However, the performance of thin and short stem cuttings also needs to be determined as their use would enable more browse trees to be established from the material grown in tree nurseries.

Competition for water and nutrients are the main environmental factors that influence tree and understorey growth in agroforestry systems (Ong *et al.* 1991; Szott *et al*. 1991; Sharrow 1999). Efforts to reduce competition between trees and understorey pasture need to be pursued to ensure less competition between these components in practical systems and at the same time increase total land productivity. To reduce understorey pasture competition, several methods have been practised including use of herbicide (Sharrow 1999), livestock grazing (Sharrow *et al*. 1992), and mowing (Lewis 1985). Herbicides used need to be safe to the fodder trees and regrowth of understorey pasture species needs to be reasonable to increase the total fodder available. Methods of pasture management need to be evaluated to identify those that minimise competition between tree and understorey pasture, particularly during establishment, and ensure high growth and biomass production.

Measurement of soil water content and plant water status is required to ensure establishing stem cuttings are not adversely affected by water stress. Early detection of water deficits, particularly during forecast dry conditions, is important for tree survival, growth and biomass production. Managing understorey pasture to give an advantage to the tree through conserving soil water and reducing water loss through evapotranspiration, is an important agronomic objective.

The effect of livestock grazing on establishing trees is another factor that needs understanding because injuries to trees can cause higher tree mortality and consequently slow regrowth. Ringe *et al*. (1984) found reduced tree survival and growth of seedling Virginia pine (*Pinus virginiana*) from livestock grazing. However, no effect of livestock grazing on slash pine (*Pinus elliottii*) was observed (Cutter *et al*. 1999). The significance of livestock grazing on the survival and growth of establishing willow and poplar trees has received

negligible scientific attention but anecdotal evidence suggests small willows and poplars are killed by grazing during the first spring and summer of their establishment.

Information on willow/poplar-pasture agroforestry or block planting, especially with regards to management of trees during establishment and the effect on growth and biomass production, is required to achieve sustainable fodder /conservation trees in New Zealand.

The main objectives in this thesis are:

(i) *To determine the effect of stem cutting size (length and diameter) of willows and poplars on tree establishment and biomass production.*

(ii) *To determine the effects of understorey pasture management and sheep grazing on soil water content, biomass production and tree damage of willow and poplar.*

Details of the experiments are presented in Chapters 3 to 7. In Chapter 3, the experiment determines the effects of understorey pasture management on survival, growth and biomass production of willow. In Chapter 4, the experiment focuses on the effect of stem diameter of willow and poplar, and planting depth, on tree establishment, growth and biomass production. The experiment in Chapter 5 determines the effect of horizontal planting of varying stem lengths and planting depths of willow and poplar on establishment and biomass production. The effect of understorey pasture management on soil water content and water status of willow in a willow-pasture agroforestry system is determined in Chapter 6. The effect of sheep grazing on young willow and poplar is described in Chapter 7. Chapter 8 contains a general discussion of results, and conclusions.

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2 LITERATURE REVIEW

CONTENT

2.1 Introduction

Pasture is generally nutritious to all types of animals including sheep and dairy cows. However in areas prone to summer/autumn drought, the nutritional quality and quantity of pasture frequently declines during these seasons. Therefore, there is considerable interest by farmers in identifying suitable alternative/supplementary sources of feed for their livestock. Willow and poplar foliage is a useful alternative source of nutritional supplementation during periods of drought (Kemp *et al.* 2003). Although willow and poplar have been planted mainly for soil conservation in pastoral hill country, they have been used by some farmers in New Zealand to feed their livestock during dry summers (Charlton *et al*. 2003). More farmers are becoming interested in growing willow and poplar as a supplementary feed source for their livestock. This interest has stimulated research to determine the best approaches to establish willow and poplar, particularly with respect to high survival and shoot DM production.

This chapter reviews aspects of willow and poplar establishment, production and their role/interaction in tree-pasture systems. This information and understanding provide the background and framework for the thesis research outline. Sections 2.2 and 2.3 review current knowledge of willow and poplar agronomy particularly factors that influence establishment and production. Section 2.4 focuses mainly on below-ground and above-ground competition and water balance as it influences tree growth in a willow/poplar-pasture system.

2.2 Willow (*Salix* spp.)

2.2.1 Experience in New Zealand

Integration of pasture, trees and livestock, referred to as a silvopastoral system, has been recognised in New Zealand since 1969 (Hawke & Knowles 1997). Willows are being planted mainly for soil conservation on pastoral hill country (Wilkinson 1999; Cameron 2003) and for river bank protection (van Kraayenoord *et al.* 1986; Wilkinson 1999). Recently willows have been studied as a component in a silvopastoral system (Stace 1996, 1998) because they

have impressive root development (Hicks 1995) which helps reduce erosion on pastoral hill country.

The feeding of tree fodder to farmed animals is common practice in many countries including New Zealand (Olsen & Charlton 2003), Australia (Newsholme 1992; Anon 2005) and Bhutan (Wangdi & Roder 2005). The use of trees for supplying feed on New Zealand farms during drought has been practised sporadically for many years, after farmers found that tree pruning provided useful supplementary feed during summer droughts (Charlton *et al.* 2003). According to Charlton *et al.* (2003), an effort is being made by regional councils in the southern North Island to increase planting of willow and poplar in silvopastoral systems. The average annual supply of planting material to farmers for soil conservation and fodder purposes includes 15,000 poles/wands from Horizons Regional Council, 20,000 poles from Hawke's Bay Regional Council, and 26,000 poles from Greater Wellington Regional Council.

2.2.2 Species and distribution

Willow, genus *Salix*, belongs to the *Salicaceae* family and members are all angiosperms. Members of the *Salicaceae* are dioecious woody plants, the wholly male or wholly female flowers being arranged in catkins (FAO 1979). Willows originated in the warm temperate region or sub- tropics and expanded mostly into the temperate regions and Arctic (Newsholme 1992). Eventually, various species became distributed to every part of the world i.e. British Isles, Europe, Asia, Japan, China, North America, Canada, India, Australia, and New Zealand. According to Cook (2003) the willow genus comprises many tree and shrub species. There are about 335 species in the world with two genera, *Salix* (willows) and *Populus* (poplars).

Willows are normally found along stream courses or in wetland communities (Cook 2003) and most species prefer moist and cool sites. In New Zealand, several species including *Salix babylonica, S. fragilis, S. alba* var. Vitellina, *S. cinerea and S. viminalis* were introduced by the early settlers between 1840 and 1880 and by the end of the 19th century, S. *fragilis* was widespread and commonly used in early river protection works (van Kraayenoord *et al.* 1986).

In 1937 Christchurch Botanical Gardens imported willow from Kew Gardens consisting of over 60 species and varieties, and they were established widely throughout the country for river bank protection and wide-row planting in tree-pasture systems for soil erosion control (Wilkinson 1999).

2.2.3 Description of *Salix* species in the study

2.2.3.1 *Salix kinuyanagi* (Kinuyanagi willow)

Willow clone 'Kinuyanagi' (Photo 2.1) is classified as an osier shrub willow. It has great potential for supplying animal fodder (Slui 1990) and grows fast on moist, fertile sites (Anon 2003). This willow is represented in New Zealand by a single male clone which was imported from the United Kingdom, coded PN 386 (Douglas e*t al.* 1996). Plant size varies from large shrub to small spreading tree and leaves are silvery underneath. The species performs well as a coppice, forage species and fuel wood (Anon 2003). In the lower North Island of New Zealand, Douglas e*t al.*(1996) found that the edible forage (leaf + stem < 5 mm diameter) had high lignin content (67-75 g/kg DM), moderate nitrogen content (21 g N/kg DM) and low organic matter digestibility (OMD) (460 g/kg DM). High total condensed tannin content (Oppong e*t al.* 1996) in plants reduces palatability to livestock in mid summer. Dry matter production was 1.71 t/ha and 0.14 t/ha for moist and dry sites, respectively, 1.5 years after planting (Douglas e*t al*. 1996).

Photo 2.1 View of willow clone 'Kinuyanagi' at Moginie Massey University (3 years old).

2.2.3.2 *Salix matsudana* Koidz. *x alba* L. (Tangoio willow)

Willow clone 'Tangoio' (Photo 2.2) is classified as a tree willow and is recommended for shelter and soil conservation (Anon 2003; Hawke's Bay Regional Counsel 2003). It is a reasonably drought-tolerant hybrid which was developed in New Zealand and released in 1980 for farm and horticultural shelter, coded NZ 1040 (Hathaway 1986b). According to McCabe *et al*. (1988), the species is palatable to cattle, sheep, goats and deer and suitable for planting on hillsides. Edible DM production 1.5 years after field establishment was 1.12 t/ha and 0.3 t/ha for moist and dry sites, respectively (Douglas *et al*. 1996). Kemp *et al*. (2003) found DM production per tree depended on diameter at breast height (DBH) of the tree. Predicted edible DM yield ranged from 1 kg for 5 cm DBH to 66.5 kg for 32 cm DBH.

Photo 2. 2 View of willow clone 'Tangoio' at Moginie Massey University (3 years old).

2.2.4 Utilisation of willow

Willows can be used for production of basket furniture, charcoal and wood pulp for the paper industry (Newsholme 1992). The tree has some medicinal properties such as salicin - a pheonolic glycoside that can be extracted for fever medication. It has now been superseded by synthetic production of aspirin containing salicylic acid (Newsholme 1992). Some *Salix* species provide good fodder for ruminants (Douglas *et al.* 1996; Fung 2001; Douglas *et al.* 2003). Willows are also widely used in New Zealand for soil erosion control on pastoral hill country (Wilkinson 1999) and riparian margins of rivers.

2.2.5 Factors affecting establishment and production of willow

2. 2.5.1 Climate

Willows can tolerate a range of climatic conditions but areas with low soil water availability should be avoided to ensure the maximum tree growth and production. According to Tubby *et al.* (2002), in low rainfall areas, water

conservation should be considered before planting. Amstrong (1999) estimated annual yields of 20 t DM/ha in research plots of poplar and up to 17 t DM/ha for certain willow varieties in Forest Commission site yield trials in USA. However, these production levels occurred only on the best sites, low nutrient or water availability likely reduced these yields significantly. Stephens *et al.* (2001) found that biomass production was intimately related to water use in crops. They showed that, in drier eastern areas of England, water stress likely reduced biomass production of willow below the climatically determined potential yield in many years. In six years out of ten years at Silsoe, the predicted 90-120 mm reduction in evapotranspiration due to water stress could result in a reduction in annual above-ground biomass production of willow of 4.5-10 t DM/ha.

2.2.5.2 Soil conditions

Soil properties are important for the successful and sustainable production of willow biomass. According to Abrahamson *et al*. (2002), willows grow best on good agricultural soils, but can also be grown successfully on soils that are marginal for traditional crops (Table 2.1). Willow growth is good on sites with large rooting volume, water and nutrient availability and good aeration. For timber production purpose (e.g. *Salix alba* var. Coerulea), *Salix* should be planted on soil of neutral or slightly alkaline pH, while dwarf species flourish on more acid soil (Newsholme 1992). In general, willow species do not prefer limed soil, which needs to be neutralized with organic matter such as compost, peat or manure. *Salix* spp. grow best on deep, moist and rich soil including mixtures of silt and clay (Hawke's Bay Regional Counsel 2003). Willows should not be planted on wet or dry soils. Very gravely soils that drain quickly and have low organic matter content, are generally unsuitable for willow due to inadequate water supply (Tubby & Armstrong 2002). Good soil aeration is required for successful willow root development (FAO 1979).

Table 2. 1 Soil characteristics suitable for growing willow biomass crops (Abrahamson *et al*. 2002).

Soil characteristic	Suitable	Unsuitable
Structure	Loams, sandy loams, loamy sands, clay loams and silt loams.	Coarse sand, clay soils
Structure	Well developed to single grain structure	Massive or lacking structure
Drainage	Imperfectly to moderately well drained	Excessively or very poorly drained.
pH	5.5 to 8.0	Below 5.5, above 8.0
Depth	45 cm or more	Less than 45 cm

2.2.5.3 Willow planting material

Planting material is important for successful establishment and biomass production. In the natural habitat, propagation of trees and shrubs occurs in two ways i.e. (i) sexual by seed, and (ii) asexual by small twigs that produce roots after falling to the ground (Newsholme 1992). However the most common method to establish fodder trees such as *Salix* and *Populus* and *Gliricidia sepium* (Shelton 1994) is through either rooted or unrooted stem cuttings. Oppong (1998) studied the effect of rooted and unrooted planting stock of two clones of willow ('Kinuyanagi' and 'Tangoio') and found that their DM yields were not significantly different. The use of unrooted stem cuttings as a planting stock is now widely practised. One advantage of using stem cuttings is greater uniformity and conformity to the selected variety of the species (Newsholme 1992). Zsuffa (1992) stated that unrooted cuttings are often preferred to rooted cuttings because they are inexpensive and easy to handle. According to Newsholme (1992), the three disadvantages of using seed are: (i) the plants are normally difficult to identify until detailed botanical tests are carried out, (ii)

plants from seed are usually slow to establish and (iii) the small seed size limits resources available for the establishing seedling.

The factors affecting the rooting of stem cuttings are either internal or environmental. Internal factors that influence rooting are genetic, morphological and physiological characteristics (Zsuffa 1992). Light, air, temperature and moisture (Newsholme 1992; Zsuffa 1992) are the main environmental influences on stem rooting. The current recommendation is to soak willow and poplar stem cuttings in water for 24-48 hours before planting to stimulate rooting and sprouting (Volk *et al.* 2001). The presence of moisture is important during propagation or planting as stem cuttings die easily and become desiccated (Newsholme 1992). Good aeration around the base of the cutting is important to ensure formation of calluses and the production of roots at the bottom of the cutting. This leads to increased cambial activity, resulting in increasing respiration from the tissues (Newsholme 1992). High soil water content and saturated soil can have a negative impact on root growth of poplar clones ('Tristis' and 'Eugenei') (Pregitzer *et al.* 1990). Pregitzer *et al*. (1990) found that a high water treatment reduced the biomass production of poplar. Soil pH influences nutrient availability and is strongly correlated with root distribution of *S. dasyclados* on peat soil (Volk *et al.* 2001). A pH above 4.5 with good moisture supply resulted in good root growth. Volk *et al*. (2001) reported that when lime was added to a peat soil and it raised soil pH from below 5 to about 6, root development of *S. viminalis* increased.

The other factor that influences successful establishment is stem cutting size. Establishment of willow can be achieved by vertical or horizontal planting. Douglas *et al*., (2003) found that total shoot DM, regrowth shoot length, and canopy width of willow were higher for trees established from 2 m poles than 1.1 m stem cuttings at a cutting height of 0.5 m and above. However no research was conducted on the effect of stem cutting diameter on shoot DM and this needs to be determined to ensure maximum production is achieved.

2.2.5.4 Willow planting distance

Willow planting distances depends on the reasons for planting. For biomass production with cutting cycles of 1 to 3 years, spacing of 0.6 m x 1.3 m to 1.3 m x 1.3 m are used (USDA 1998). In Britain, most commercial willow crops are established at a spacing of 0.75 m between rows and 1.5 m between twin rows with 0.6 m between stem cuttings giving a density of 15,000 trees/ha (Tubby & Armstrong 2002). In New Zealand, Douglas *et al*. (2003) used 2 m x 3 m spacing (1670 stems/ha) in a willow coppice block in Hawke's Bay, and 1.2 m x 1.2 m (6,900 stem/ha) in a browse block in the Wairarapa in New Zealand.

2.2.5.5 Fertiliser application

Tubby *et al*. (2002) stated that a positive response to fertiliser application is not guaranteed. These workers also reported that work carried out by Yorkshire Environmental Limited in 1996, found that willow receiving sewage sludge or inorganic fertiliser over the first few years did not yield significantly higher than those which were not fertilised. This may have been because of the naturally high fertility of the site. However, Snow *et al*. (2003) showed that willows responded to applications of dairy effluent with trees receiving low, medium and high effluent rates producing 6, 13 and 24 t DM/ha, respectively. In Manawatu, willow fodder blocks have established successfully without fertiliser applications.

2.2.5.6 Weed management

Effective weed control is essential for the successful establishment of many trees and shrubs such as willow and poplar (Abrahamson *et al*. 2002; Tubby & Armstrong 2002), and tree legumes (Shelton 1994). According to Shelton (1994), slow and unreliable establishment of trees increases the time and level of risk before economic returns are feasible, and farmers are much less likely to adopt new technology when establishment risks are significant. Currently available willow clones do not compete well with weeds during the establishment year, or during the first part of the second growing season (Abrahamson *et al.* 2002). Weeds are not a major problem once the canopy of a tree touches others (Abrahamson *et al.* 2002). According to Abrahamson *et*

*a*l. (2002) willow yield will be much lower during the first rotation, if weeds are not controlled, or in the worst case, the planting may have low survival and never be productive. Maasdrop *et al*. (1986) showed that legume fodder shrubs markedly suppressed seedling growth and yield of *Sesbania* species when weeds were not controlled effectively. A completely weed-free site is required at planting and must be maintained until crop foliage shades out the weeds (Tubby & Armstrong 2002). Weed control can be divided into three phases: before cultivation, shortly after planting, and after cut-back or harvesting (Tubby & Armstrong 2002). Before cultivation all perennial weeds should be controlled by broad-spectrum herbicides such as glyphosate, and residual soil-acting herbicides should be sprayed once the crop has been established to control germinating weeds. Appropriate residual herbicides are essential for control of rapid and profuse growth of weeds in fertile sites after planting to maximize tree survival and early growth (Tubby & Armstrong 2002). After cut-back or harvesting willow, the site should be sprayed with contact herbicide mixed with a residual herbicide to control both established and subsequently germinating weeds (Tubby & Armstrong 2002). Study by Gilchrist (1979) on the effects of various herbicides on tree survival and the elongation of stem during first year of willow establishment found that hybrid Pekin willow (*Salix matsudanas* x *S. alba* - NZ 1002) and purple osier willow (*S. purpurea*) were tolerant to residual herbicide (Atrazine, terbumeton, simazine, alachlor, dichlobenil and diphenamid).

2.2.5.7 Pests and diseases

Willow can tolerate a relatively high level of leaf damage with little adverse effect, but severe attacks reduce yield (Tubby & Armstrong 2002). The most significant insect that affects willow in New Zealand is sawfly (*Nematus oligospilus*). Sawfly at the larval stage can damage leaves and severe defoliation of trees can kill them. The application of insecticide in the early stage of infestation is important to avoid further damage.

According to Charles *et al.* (1998), sawfly larvae have been found on at least the following willows in New Zealand:

Common name	Scientific name
Crack willow	*Salix fragilis*
Twisted, corkscrew, or tortured willow	*S. matsudana* 'Tortuosa'
Peking or matsudana willow	*S. matsudana*
Weeping willow	*S. babylonica*
Pencil willow	*S. humboldtiana* cv 'Chilensis'
Golden willow	*S. alba* var. 'vitellina'

Hybrid willows such as *S. matsudana* x *S. alba* (e.g. 'Tangoio', 'Moutere', 'Aokautere'), and natural hybrids of golden and crack willow, are also attacked. Willow sawfly has not been found on any species of *Populus*. The other insects that affect willow are beetles of the chrysomelid family, mainly brassy and blue willow beetles (*Phratora* spp.) (Tubby & Armstrong 2002). *Melampsora* rust is a common fungal pathogen which attacks both willow and poplar. Willow is susceptible to a number of different species of rust, of which *Melampsora epitea* is the most important in United Kingdom (Tubby & Armstrong 2002). Using rust-tolerant varieties is recommended to solve this problem (Tubby & Armstrong 2002). However this rust disease is not a widespread problem in New Zealand.

2.2.6 Willow production

Willow biomass production in fodder blocks ranges from 2.7 to 30.8 t DM/ha/yr depending on climate, soil type and fertility, tree age and plant density, plant size and harvesting cycle (Hathaway 1980, 1986c). At dry and moist sites in the lower North Island, willow 'Tangoio' at a planting density of 2700 trees/ha and under various cutting heights and cutting frequencies, yielded 1.2 to 4.3 t DM/ha/yr, of which about 25% was edible (Douglas *et al.* 1996). Douglas *et al.* (2003) also found that the effect of cutting length (1.1 m to 2 m) and cutting height (0.25 m to 1.5 m) on biomass production ranged from 0.12 to 2.29 t/ha/yr, of which 30-50% was edible. However, Abrahamson *et al.* (2002) reported that yields of fertilized and irrigated willow for three years have

exceeded 12 t DM/ha/yr, while the first rotation of unirrigated willow produced 5 t DM/ha/yr and yields increased by 35 to 100% in the second rotation. However yield will be increased by optimizing various components of the production system such as weed control and fertilisation (Abrahamson e*t al.* 2002).

2.3 Poplar (*Populus* spp)

2.3.1 Poplar species and distribution

Poplar, genus *Populus* belongs to the *Salicaceae* family and the trees are classified as angiosperms (FAO 1979). Poplars are dioecious woody plants, on which male and female flowers are arranged in catkins (Bean 1977; Rauzin 1978; FAO 1979). According to FAO (1979) members of the *Salicaceae* are widely distributed in the northern hemisphere, from the polar circle to latitude 30^{o} N and even occur in the southern hemisphere. Poplars are native to Europe, North America and China (Reid & Wilson 1985). They are easy to grow and propagate, and have been planted extensively as street trees and for reforestation (FAO 1979). According to Wilkinson e*t al*. (1992), the trees prefer moist soil and are often found along stream banks. Poplars require at least moderate soil water throughout the growing season (Miller & Wilkinson 1995) and although they are tolerant of a wide range of soil types, they grow well on deep loamy soils.

2.3.2 Poplar species introduced in New Zealand

Populus nigra Italica (Lombardy poplar) and *P. deltoides* (Cotton wood poplar) were first introduced to New Zealand between 1840 to 1850 (van Kraayenoord 1993). *Populus nigra* originates from Eurasia and grows up to 27 m tall, *P. deltoides* originates from America, and can grow to more than 30 m in height and 1.2 m in trunk diameter (Kennedy 1985). *Populus deltoide*s and *P. nigra* have been used mainly for soil conservation and amenity purposes in New Zealand (Miller & Wilkinson 1995). Other uses of these species include shade, windbreak, ornamental, fibre, plywood, and special products (Beaton 1987; Eyles 1993; Wilkinson 1993; Quam 1997). The main cultivars currently available in New Zealand are shown in Table 2.2.

Table 2. 2 New Zealand Poplar Cultivars (Stace 1998).

Species/Hybrid	Cultivar	Characteristics	Basic Density (kg/m^3)	Uses
Populus alba x glandulosa	Yeogi	Resistant to rusts, leaf spot, possums. Good tolerance of drier, saline soils, limited tolerance to wet soils. Suckering habit. Yeogi is Male clone.	390	Soil conservation, forestry and agroforestry.
Populus deltoides x maximowczii	Eridano	Fast growth. Resistant to rusts and leaf spot. Highly unpalatable to possums but large leaves and brittle branches. Susceptible to wind damage. Male clone.	350	Soil conservation, agroforestry and amenity.
Populus deltoides x trichocarpa	Pakai	Good possum resistance but slight susceptibility to frost in juvenile stage. Limited bud wood can cause some variation in strike. Male clone.	370	Soil conservation, agroforestry.
Populus deltoides x yunnanensis	Kawa	Faster growth and better form than parent *P. yunnanensis*. Moderately susceptible to wind and possums, disease resistant. Male clone.	330	Soil conservation, shelterbelt, agroforestry, amenity
Populus euramericana (*Populus deltoides* x *nigra*) (import)	i. Tasman ii. veronese	Both clones are moderately susceptible to leaf spot and are possums palatable. Tasman is resistant to rust while Veronese is moderately susceptible. Tasman is a narrow crown. Male clone that requires moist sites. Veronese is a female clone with a degree of drought tolerance.	330	Soil conservation, agroforestry, and amenity.
Populus euramericana (NZ bred)	Argyle, Eastwood, Kaianga, Margarita, Pakaraka, Weraiti.	Argyle and Eastwood form broad crowns and Argyle has early formation of heavy bark. All are palatable to possums and have good disease resistance except Margarita which has slight susceptibility to rust in late summer. Kaianga is a female clone. All others are male clones.	330-340	Soil conservation, shelterbelts, and agroforestry.
Populus euramericana yunnanensis	Toa	Resistant to rusts and leaf spot. Low palatability to possums, fast growth rate. Female clone.	320	Soil conservation, shelterbelts

2.3.3 Poplar planting and establishment

2.3.3.1 Planting stock for field planting

Poplars can be established on suitable sites through natural seed-fall or from stem cuttings. Most commercial strains of poplar are reproduced vegetatively by stem cuttings taken from ripened wood (FAO 1979). Cuttings are taken from long shoots during the dormant season. The shoots can be taken from stools, pollards or from young plants (1 yr) or from vigorous vertical branches in the tree crown (FAO 1979; Radcliffe e*t al*. 1990). In the USA, it is recommended to use cuttings of diameter 1.0-2.5 cm harvested from one-year old shoots during the dormant season (USDA 1998). Length of stem cuttings can be varied from 20 cm to 180 cm depending on the objectives and site of planting. In lowland areas with low summer water tables (45 cm to 90 cm) or sites requiring irrigation, the USDA (1998) suggests planting 20 cm to 30 cm long cuttings with one bud above the ground. At sites where the water table is deeper than 90 cm, longer stem cuttings are recommended to be planted at 60-180 cm depth. In New Zealand, 3m poles, rooted cuttings (1.5 to 2 m long), and 1m stakes are normally used for establishing poplar (Evans 1973; Hathaway 1986b, a; Stace 1998) and cuttings are normally planted at a depth of 25-35 cm (Evans 1973). Beaton (1987) recommended the practice of deep planting (> 35 cm) to ensure stability of developing plants and satisfactory soil water content.

Key factors affecting propagation of poplar by stem cuttings are:

(i) Age of shoot cutting: Cuttings harvested from young trees especially from one or two year-old shoots produce the best cuttings provided the shoots are taken from the lower two thirds of the terminal ends of shoots. Young shoots more readily produce roots than old trees (FAO 1979).

(ii) Season of harvesting cuttings: Experiments on propagating *P. deltoides* in the United States found cuttings taken from October to March (autumn/winter) had the greatest rooting potential (FAO 1979). However, from observation most of the growers in New Zealand harvest over a shorter period in winter (June or July before bud sprouting). Further study

is needed to determine the optimum harvesting time of cuttings which root easily.

(iii) Environmental factors: Temperature and soil water content influence rooting characteristics of poplar cuttings. In Canada, a temperature of 21 ^{o}C was the optimum for the rooting of cuttings of *P. tremuloides*, while in Italy the optimum was 27 ^{o}C for *P. tremuloides* cv. 'Harvard'. (FAO 1979). However, according to Lyr *et al*. (1967), the effect of soil temperature on root growth of plants is complicated because growth intensity of roots depends not only on temperature, but other factors such as soil water content and shoot activity (carbohydrate supply), which are influenced by light, air temperature, humidity and root activity. Soil water content is important for poplar root production. FAO (1979) stated that there were marked differences in root production of poplar (American clones) on different soil water contents for example between 80 and 100%.

2.3.3.2 Choice of site

Poplars generally prefer moist, and fertile sites for good establishment and growth, and some varieties are able to tolerate dry or windy conditions (Fung 2001). In the USA, poplar grow well in well-drained soils such as sandy loams or silt loams (USDA 1998). The trees can also grow in clayey, poorly-drained soil, but exhibit poor performance in terms of growth and yield. Poplars can tolerate short periods of flooding when they are dormant but are intolerant of flooding during summer. The water table in summer should be at a soil depth of at least 45 cm.

2.3.3.3 Poplar tree spacing

Tree spacing will depend on target diameter, buffering or site remediation needs, maintenance methods and product goals (USDA 1998). Short rotation plantings with a cutting cycle of 1 to 3 years are spaced at 60 cm x 120 cm to 120 cm x 120 cm, for fibre production, while cutting cycles of 6 to 7 years are spaced at 240 cm x 240 cm, 270 cm x 270 cm or 210 cm x 300 cm (USDA

1998). In New Zealand, planting density of poplar in silvopastoral systems is 25-150 trees/ha (Wilkinson 1995) and up to 200 trees/ha for timber production (New Zealand Poplar Commission 1995).

2.3.3.4 Time of planting.

In a relatively mild climate, planting can usually be conducted through the entire dormant season, except during spells of frost. Planting can be commenced as soon as leaves have fallen, if the weather is fine in autumn. However, in the case of clones that mature late and are susceptible to *Dothichiz*a spp., planting in spring provides a better chance of their rooting (FAO 1979). In areas where the winters are particularly cold, planting in spring is recommended (FAO 1979), beginning when the soil temperature reaches 10 ^{o}C (USDA 1998). According to Horizons Regional Council (2006), the best time to plant poplar is from late June to early August to maximise the change of high plant survival. Cuttings should be soaked in water for 24 hours before planting, if planting in late spring (USDA 1998).

2.3.3.5 Maintenance

Good site preparation and effective weed control are important to ensure successful establishment and fast growth of poplar. Herbicides such as glyphosate can be applied to kill grasses and other vegetation followed by deep tillage or ripping to allow easier planting and better root development (USDA 1998). Weed control between and within rows is achieved by applying pre-emergent herbicides or shallow tillage for at least 2 to 3 years until canopy cover. For short rotation blocks of willow and poplar, legumes or non-rhizomatous grasses can be used between the rows in the early years providing they are mowed to reduce tree competition for root development (USDA 1998). Poplars need effective weed control during the first year to maximise growth potential (Radcliffe *et al*. 1990). Gilchrist (1979) found simazine and propazine herbicides are likely to be tolerated by BO2 silver poplar (Populus alba) and Flevo hybrid black poplar (*P. euramericana* 'Flevo 923') during the first year of tree establishment.

The effectiveness of using fertiliser is still in debate and largely depends on the fertility of the site. On light poor soils, application of a nitrophosphate fertiliser generally gives positive results, however fertiliser trials on fertile soil have rarely shown any economic justification (USDA 1998). In France (USDA 1998), fertiliser has been applied around each stem such as ammonium phosphate, equivalent to 0.5-1.0 kg/tree/season of a binary fertiliser formula 10:20:0 (N:P:K).

2.3.3.6 Poplar production.

Yield of poplar in the United Kingdom has ranged from 4.9 to 15.9 t DM/ha/yr in the first year of rotation, depending on site and variety, and increased up to 21.3 to 41.7 t DM/ha/yr for the third year of rotation (Tubby & Armstrong 2002). Kemp *et al*. (2003) developed an equation for predicting edible biomass production of poplar clone 'Veronese' based on diameter at breast height (DBH). Biomass production of trees of DBH 5-24 cm ranged from 0.9 kg to 23.4 kg/tree (Kemp *et al*. 2003).

2.4 Agroforestry

The International Centre of Research on Agroforestry defines agroforestry 'as a dynamic, ecologically based, natural resource management system that, through the integration of trees on-farm and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits for land-users at all levels'(ICRAF 2003). In New Zealand agroforestry has been defined as "a land-use system which combines wide spaced trees with livestock or cropping enterprises" (Reid & Wilson 1985). In more recent years, definitions of agroforestry in New Zealand have widened to include a mix of species at several densities grown for a variety of purposes.

Although definitions vary, characteristics of agroforestry usually possess the following features: (i) agroforestry usually comprises two or more species of plants of which at least one is a woody perennial, integrated on one piece of land, (ii) agroforestry always has two or more outputs, (iii) agroforestry is a land management system, and (iv) agroforestry is a form of maximum land use, (v).

agroforestry is more complex, ecologically and economically, than a monocultural system (Mahmud 2001).

2.4.1 Willow and poplar agroforestry

Poplar and willow are well-suited for agroforestry in many countries such as in the United States (USDA 1998), and New Zealand (Cameron 2003; HortResearch 2003). According to Dupraz *et al*. (1997), farmers in many countries are growing agricultural crops between rows of young poplar and this system has performed well for many years. In Italy, combinations of poplar with pasture are sustained for up to three to four years until the trees are well developed (FAO 1959). In New Zealand, farm forestry or agroforestry has been practised since the 1960s (The New Zealand Forestry Association 2001) for soil conservation, shelter on pastoral and horticultural farms (Hathaway 1986c, b) and for supplementary fodder (Douglas *et al*. 1996). Poplars and willows are chosen because of their ease of establishment, fast growth and effectiveness in decreasing soil erosion. In more recent years the fodder value of these trees has been widely recognised.

2.4.2 Willow and poplar as fodder

Trees and shrubs can be used as supplementary fodder for grazing livestock, particularly during dry summers (Lefroy 1992) when pasture production and quality are reduced. Poplar and willow trees are less affected by dry conditions because of their extensive root systems and long leaf life-spans. Fodder or browse is defined as the shoots or sprouts, especially tender twigs and stems of woody plants, with their leaves (Torres 1983). The use of fodder in agroforestry depends on specific needs of the system.

Many regions of Australia and New Zealand experience a seasonal dry period each year and fodder trees and shrubs provide an alternative fodder source at this time (HortResearch 2003). According to Fung (2001), poplar and willow are suitable for fodder because of (i) their fast growth, (ii) an ability to root from poles and, (iii) coppicing ability. Previous work, as well as that currently undertaken by Massey University and AgResearch has indicated that both

poplar and willow are suitable fodder sources for sheep, cattle and deer (Fung 2001). The major tree willows suitable for fodder include (i) Golden willow (*S. alba* var. 'vitellina') and hybrids, (ii) Crack willow (*S. fragilis*) and hybrids, (iii) 'Matsudana' willow (*S. matsudana),* and (iv) 'Tangoio' (*S. matsudana* x *S alba*) and other similar hybrids such as 'Moutere' and 'Makara' (Fung 2001). Total shoot DM production of *Salix* spp. has been determined and reported in several publications such as in New Zealand (1.0-9.9 t DM/ha) (Douglas *et al.* 1996) and Bhutan (3.8-7.0 t DM/ha) (Roder 1992). The organic matter digestibility (55-65 %) and metabolisable energy content (8 -9 MJ/kg DM) of willow and poplar forage are similar to normal pasture, or greater than summer/autumn drought pasture (Kemp e*t al.* 2003). Fung (2001) reported poplars commonly classified as black poplars are palatable to sheep and cattle. Some farmers in New Zealand use willow and poplar to feed sheep during dry summers (Charlton *et al.* 2003) and freshly senesced poplar leaves have high concentrations of some minerals (McGregor 1989).

2.4.3 Effect of planting trees on understorey pasture

Planting trees in a pastoral system reduces the extent and severity of soil erosion, but at the same time it can adversely affect pasture production and composition, and consequently livestock performance. For example, in a silvopastoral trial involving *Pinus radiata* at densities of 250, 500, 1000 and 2000 stems/ha at Tikitere New Zealand (McQueen e*t al.* 1976; Hawke & Wedderburn 1994), pasture yield decreased with increasing tree density and age. At densities of 200 and 400 stems/ha, pasture yield declined rapidly once canopy closure occurred, while at 100 stems/ha, pasture production was not reduced until 8 years after tree establishment. On the East Coast of the North Island, New Zealand (Gilchrist *et al.* 1993), annual pasture yield near trunks of established poplar, willow and eucalypt trees was 10% less than in the open (no trees). Low pasture production under mature space-planted poplars was also found by Wall *et al.* (1997) and Guevara-Escobar *et al.* (1997).

2.4.4 Effect of agroforestry on microclimate changes

The most important effect of combining woody and non-woody plants in the same land area is the modification of microclimate which affects the growth of all components in the system. Tree canopies modify light, temperature and moisture extremes. During daylight, canopies shelter the soil surface from solar radiation and at night they decrease heat losses, thus narrowing the amplitude of daily temperature variation. According to Wallace (1996), tree canopies in an agroforestry system can modify microclimate through reducing or altering the kinetic energy of incident rainfall which in turn influences susceptibility to soil erosion. Temperature and light intensity are also altered under agroforestry systems. Guevara-Escobar *et al*. (1997) found that light intensity and soil temperature beneath mature poplar trees were lower than in the open (no trees), which resulted in decreased pasture production. Hawke *et al*. (1994) examined the integration of *Pinus radiata* and pasture with regard to microclimate changes, and found that wind speed reduced with increasing tree density (100, 200 and 400 trees/ha). The agroforestry system also increased the pasture minimum temperatures at all planting densities but decreased soil temperature at densities of 200 trees/ha and above (Hawke & Wedderburn 1994). The effect of microclimate may be favourable for livestock farming. Solar irradiance was 31% less under a poplar-pasture intercrop compared to open pasture (Douglas *et al*. 2001) which provides shade for grazing livestock particularly sheep during hot, dry periods.

2.4.5 Competition effects in agroforestry

Plants in polyculture compete for limited resources such as light, soil moisture and nutrients (Sharrow 1999). Tree and understorey crops/pasture compete both below- (soil moisture and nutrient) and above-ground (light). Tree-crop/pasture integration which has been observed in many alley-cropping or tree/pasture trials has resulted in decreased crop/pasture yields (Sing *et al.* 1989; MacLean *et al*. 1992; Guevara-Escobar *et al*. 1997; Cossens & Hawke 2000; Douglas *et al*. 2006).

2.4.5.1 Below-ground competition

The main below-ground competition in agroforestry systems is for soil water and nutrients (Sharrow 1999). In a silvopastoral context this competition will influence growth and production of tree and pasture components. Forage plants with fibrous root systems grow quickly during the growing season and compete strongly for soil resources in the 0-15 cm soil depth which has reduced establishment and growth of young conifers, particularly in a dry season with shallow soils (Nambiar & Zed 1980). Sharrow (1999) recommended suppressing pasture competition in the first 2 years of tree establishment in a silvopastoral system. This can be achieved by circle (1 m radius) or a 1-2 m wide strip with herbicide for a weed-free zone for tree establishment. The other effective methods to suppress weeds for tree establishment in tree-pasture intercrops are mowing (Lewis 1985) and grazing (Sharrow *et al*. 1992), but these may result in damage to the trees. According to Sharrow (1999), once the tree roots have established well under the pasture root zone, tree growth is less influenced by the effect of pasture on soil water content. Nutrients, especially nitrogen, sulfur and other nutrients related to organic matter, are plentiful in the upper soil zone. It is likely, therefore, that competition between established trees and pasture for nutrients is more important than soil water content in the surface soil profile.

According to Ong *et al*. (1996) competition between trees and crops interaction in an agroforestry system is for the same limiting growth resources (soil moisture and nutrient). Even though soil water content is commonly the main limiting factor for establishing trees, Woods *et al*. (1992) showed that nitrogen fertilization balances the impact of herbaceous weed competition on 2-3 year-old *Pinus radiata* seedlings, suggesting that competition was primarily for soil nitrogen. However, according to Sharrow (1999), numerous authors have concluded that competition between trees and crops is mainly for soil resources. Below-ground competition may differ seasonally, with competition for soil water foremost in summer and relatively greater competition for soil nutrients in spring (Sharrow 1999). In general, below-ground competition

seems to affect growth of the tree and understorey crop/pasture, more than competition for light, at least until canopy closure.

2.4.5.2 Above-ground competition

The most prominent factor for above-ground competition in an agroforestry system between trees and companion crops or understorey crops/pasture, is solar radiation. Early in tree establishment, young trees might be shaded by surrounding herbaceous vegetation. However once the tree canopy grows above the vegetation, understorey crop/pasture will compete with the trees for light and it will have a negative effect on photosynthesis. Gardner *et al*. (1985) pointed out that most C3 herbaceous plants need at least 10% of full sunlight to achieve compensation point. The leaves become light saturated when photosynthesis rapidly increases beyond the compensation point. According to Gardner *et al*. (1985), light saturation levels for warm season plants (C4 pathway) and cool season plants (C3 pathway) are about 85% and 50% of full sunlight, respectively. Reduced light intensity under a tree canopy will influence understorey temperature, and therefore low light under an agroforestry system is possibly more critical for warm season than cool season crops or pasture. Cool season crops are only affected when the trees intercept over 50% or more of the total incoming solar radiation. For shade-tolerant temperate conifers, radiation inputs must be reduced by at least 60% before the trees show any reduction of growth and morphological changes.

Lower photosynthetically active radiation (PAR) has been received by pasture beneath poplar (10-60%) (Guevara-Escobar *et al*. 1997; Wall *et al.* 1997) and beneath pine (50-60%) (Peri *et al*. 2001), compared with open pasture resulting in reduced understorey pasture production.

2.4.6 Agroforestry and efficient use of water

The success of agroforestry seems to lie with making better use of scarce resources through using more resources or by using them more efficiently, or both (Ong 2001). An agroforestry system might increase overall rainfall use efficiency indirectly by more rain being used in transpiration, or directly by

enhancing the water use ratio in agroforestry through more yield produced per unit of water transpired.

2.4.6.1 Water use in an agroforestry system

Water availability is one of the main factors that influences the success or failure of an agroforestry system (Sing *et al*. 1989). The introduction of trees to a conventional cropping or pastoral system may increase water use, through the utilisation of rainfall which cannot be used by the crop (Jackson *et al*. 2000) or, by reducing soil erosion in hilly areas (Wilkinson 1999; Cameron 2003). Increased plant water-use can also occur indirectly through modification of the understorey crop micro-climate with less water being lost by soil evaporation and thus more water is available for trees and understorey crop transpiration (Jackson *et al*. 2000). Predicted transpiration of large cottonwood (0.5 m diameter) was 200-500 litres/day, while willow which was much thinner than cottonwood, transpired between 30-100 litres/day (Schaeffer *et al*. 2000). Guevara-Escobar (1997) found average water use by poplar was 192 litres/day.

The hypothesis that sole annual crops are unable to fully exploit available water compared with agroforestry systems which may utilise larger amounts of water for biomass production has received considerable research attention. For instance, hedgerow plantings of mono-cropped *Leucaena* spp. extracted more available water than mono-cropped or mixed plantings of sorghum and pigeon-pea (Ong *et al*. 1992). Conversely, another study with widely spaced alley crops (4.4 m between hedges) indicated that more soil water was extracted than by mono-cropped *Leucaena* spp., showing that agroforestry with intercrops was more efficient in exploiting available water than annual crops (Ong *et al*. 1992). However, Corlett *et al*. (1992) reported that integration of *Leucaena* spp. and annual crops reduced crop yields by 50-80%. A similar result was found in silvopastoral systems with understorey pasture production being 40% (Guevara-Escobar *et al*. 1997) and 23% less (Douglas *et al*. 2006) than open pasture, indicating that severe competition occurred.

2.4.6.2 Water management in agroforestry systems

Water management is very important not only in agroforestry systems but also conventional agricultural systems, because water can limit plant growth and impact on nutrient cycling and soil erosion. Some researchers have proposed agricultural systems which contain multiple plant species that can exploit more resources than monocultural systems through temporal or spatial niche differentiation (Susan & Beverly 1999). Components in agroforestry systems can potentially complement each other with respect to resource use and therefore be more productive. According to Morris *et al*. (1993) there was generally no increase in total water use in an intercrop system compared with a mono-cropped system. Nevertheless, Cannell *et al*. (1996) found that the benefits of agroforestry will appear only when the trees are capable of obtaining resources of light, nutrients and water that the crop would not otherwise acquire. Agroforestry alters the microclimate and influences evaporation from plant and soil surfaces, transpiration, deep percolation, and surface runoff. Water losses from the trees vary, depending on climate, soil type, landscape and management of the cropping system. Furthermore, water can enter plant-soil systems through rainfall infiltration, and lateral movement of water beneath the surface. According to Susan *et al*. (1999), some cropping systems may be able to access more of this water than others, thus increasing the amount of water available to plants.

2.4.6.3 The water balance of an agroforestry system

Rainfall, evapotranspiration, runoff and drainage influence the soil water balance in agroforestry systems, and it is complex (Ong 2001). The gross rainfall (P_g) is first intercepted by the tree and crop canopies, giving rise to interception losses from trees (I_t) and the crop (I_c). Tree canopies modify the rainfall with changes to the water input of ground under the trees (P_t) and under the crop (P_c) due to both stem flow and throughfall. A study by Jackson (2000) in a grevillea-maize intercrop (widely spaced) indicated that tree stem flow is a very small percentage (0.7%) of gross rainfall. However, studies by Van Dijk *et al*. (2001b) revealed that in crops such as maize grown at high plant densities,

stem flow can be 2 to 4% of gross rainfall. The input of rainfall reaching the ground might infiltrate at diverse rates below the trees (F_t) and crop (F_c), yielding different rates of surface runoff i.e. R_t and R_c, respectively. According to Ong, (2001), in some conditions F_t, may be sufficiently high to absorb P_t as well as runoff (R_c) from the cropped area, resulting in total runoff from the whole plot being insignificant. This was shown in agroforestry studies on sloping land at Machakos, Kenya, where runoff was less than 2% of annual rainfall (Kiepe & Rao 1994). Evaporation will occur directly from the soil surface at rates E_t and E_c. According to Wallace (1996), the water content of the soil profile beneath the tree (θ_t) and the crop (θ_c) vary because of the diverse surface inputs and transpiration rates (T_t and T_c). This may lead to the different drainage systems, i.e. D_t and D_c. Agroforestry practices on hillsides may also affect lateral sub-surface water movement i.e. R_s, especially in high rainfall sites where the soil is saturated for significant time (Wallace 1996). The total transpiration rates of an agroforestry system (Wallace 1996) are therefore:

$$T_t + T_c = P_g - I_t - I_c\, E_t - E_c - D_t - D_c - R_t - R_c - \delta\theta_t - \delta\theta_c.$$

The total transpiration rate in a mono-cropping system is:

$$T^*_c = P_g - I^*_c - E^*_c - D^*_c - R_c - \delta\theta_c$$

where the superscript * shows that these terms can be different in the absence of companion trees. Mathematically the agroforestry system can use rainfall more effectively and therefore can be expressed as:

$$T_t + T_c > T^*_c$$

2.4.6.3.1 Rainfall interception in agroforestry systems

The effect of introducing trees into an area of crop/pasture is to reduce the net input of rainfall to the understorey through rainfall being lost by tree interception. According to Wallace (1996), some of the incident rainfall is held by the canopy and if there is an input of energy from the atmosphere or sunlight, this water can evaporate from the canopy. However, if the rainfall endures on the plant canopy and is not evaporated, it starts to flow from leaves and drip to the stem. The entire process is known as interception and it is an essential process in the water balance of many types of vegetation. The process of interception in agroforestry systems varies from a pure forest system in two main ways: (i) most agroforestry systems tend to have relatively low tree densities, and (ii) the introduction of various crop components in the system results in different canopy covers (Ong 2001). Van Dijk e*t al*. (2001a) have introduced an interception model that focuses specifically on variable crop cover. The amount of water stored in the tree canopy and the rate of evaporation from the tree canopy are the two main factors that control interception in agroforestry systems. According to Gash e*t al*. (1995) the water storage of an individual tree is largely independent of tree density and is directly associated with canopy cover and reduces to zero as cover decreases. Guevara-Escobar e*t al*. (2000) found that the percentage of rainfall intercepted by the poplar canopy in a poplar/pasture system was 34%, while Kelliher e*t al*. (1992) reported that the percentage of rainfall intercepted by forest stands of radiata pine in New Zealand was 19%. Weather conditions during precipitation markedly influence the rate of evaporation from the wet canopy, however tree density can also influence this rate with potentially higher exchange in sparser, more well-ventilated canopies (Teklehanimanot & Jarvis 1991).

2.4.6.3.2 Soil evaporation and transpiration in agroforestry

Water at or near the soil surface can be directly lost as evaporation, especially in hot or tropical areas with sparse ground cover, high radiation and frequent rainfall (Ong 2001). In agroforestry systems, tree canopies reduce radiation intensity at the ground thereby decreasing soil evaporation. According to Ong

(2001), there are two phases in the process of soil evaporation The first phase could be decreased by canopy cover and after this process, the rate of soil evaporation depends on soil hydraulic properties (second phase). The net effect of shade on the total amount of soil evaporation over time depends on the period of time the soil is in the first and second phases of drying, the soil type and the frequency with which the soil surface is re-wetted by rainfall.

Wallace *et al*. (1999) suggested that soil evaporation was reduced up to 30% because of the presence of the tree canopy. This author calibrated a simple soil evaporation model to determine the effect of shaded and bare soil on soil evaporation over 18 months. The result showed that during this period, soil evaporation decreased from 59% of rainfall for completely bare soil, to 41% of rainfall under canopy shade. The average annual reduction in soil evaporation under full canopy shade was very significant at 157 mm or 21%. In smaller sparse tree canopies the reduction of soil evaporation was 15% of rainfall when cover was 50%,and 6% of rainfall when cover was 20% (Wallace *et al*. 1999). Mulching in agroforestry systems can also influence soil evaporation by reducing wind speed and radiation at the soil surface, and the physical structure of mulches may also absorb water during rainfall, which can subsequently evaporate without entering the soil (Wallace 1996).

Transpiration is the loss of water to the air from trees. It is determined by the balance between atmospheric demand on the canopy and supply of water by roots (Kelliher *et al*. 1993). The balance between water use and water supply by roots allows trees to cope with soil water deficits.

Loss of water generally depends on air temperature, light intensity, soil water content, humidity and wind (Anon 2006) and also tree size and type of production systems such as open pasture and silvopastoralism (Guevara-Escobar 1999). Guevara-Escobar *et al*. (2000) estimated higher evapotranspiration from a poplar-pasture system (2.7-3.0 mm/day) than open pasture (2.2 mm/day). In the absence of water stress, Hall *et al*. (1998) found that the maximum transpiration rates of a poplar short rotation crop (*Populus deltoides x P. trichocarpa*) and willow (*Salix burjatica*) was 11 mm/day.

Transpiration of cottonwood and willow forests has averaged 4.8 mm/day (Schaeffer *et al.* 2000).

2.4.6.3.3 Soil runoff in agroforestry systems

When rainfall reaches the soil surface, some of it may infiltrate into the soil (Wallace 1996). If the rainfall rate exceeds the infiltration rate, excess water collects on the surface and when the surface storage is exceeded, runoff occurs. Infiltration is a dynamic process that changes during the course of a rainstorm depending on the soil characteristics, slope of the land, and rainfall intensity (Wallace 1996). According to Kiepe & Rao (1994) where the integration of woody and non-woody plants alters any of these factors, infiltration and runoff may be affected. Lai (1989) found that surface treatments also play an important role in determining runoff from agroforestry blocks. In a hedgerow planting of *Leucaena* or *Gliricidia* on a 7% slope, runoff was 64 to 80% less than from an annual crop on plough-tilled land. Other factors that influence runoff are soil characteristics including the presence or absence of plant residues, surface storage, surface crusting, and saturated hydraulic conductivity. The significant effect of vegetation cover in reducing runoff was shown in Senegal where runoff was reduced from 456 mm per year on bare soil to 264 mm per year on cultivated land and to 200 mm per year from a mixed planting of shrubs-herbs (Wallace 1996). Agroforestry alters surface infiltration through modification of canopy characteristics, which reduces rainfall kinetic energy to the ground, potentially altering crust formation and particle detachment. Incorporating plant residues into soil such as by mulching can reduce surface crusting and enhance soil hydraulic conductivity (Kiepe & Rao 1994). These can reduce soil runoff through improved soil fauna activities and improve soil structure and water holding capacity.

2.4.6.3.4 Drainage in agroforestry systems

Drainage is the loss of water below the root zone and it is difficult to quantify. Most of the water drainage losses are estimated from measurements of soil

water content. According to Wallace (1996), the amount of water that enters soil results from the combined effects of rainfall, infiltration and runoff. The soil water matrix can be re-evaporated from the surface, taken up by plant roots and under certain conditions, excess water can flow laterally and leave the bottom of the soil profile as drainage. Soil water content varies with time and soil depth (Wallace 1996). On the soil surface, water content plays a dominant role in infiltration, runoff and soil evaporation, while deeper in the soil profile, water content influences lateral water movement and water drainage.

Soil water content alters under an agroforestry system because of variation in infiltration and runoff rate under the tree and crop components. Absorption of water by roots of trees and crops also alters soil water content, which influences drainage in the system. A study by Jackson (2000) on a Grevillea-maize agroforestry system indicated that soil water content decreased by a much greater amount at depth and it was concluded that drainage from the tree/crop mixture was much less than in a mono-cropped system. Trees can affect soil water patterns via the possibility of hydraulic lift in which water taken up by plant roots from moist zones of soil is transported through the root system and released in drier soil. In an agroforestry system, transpiration and interception losses are increased with interception losses increasing 10-50% depending on the climate (Table 2.3) (Ong 2001).

Table 2. 3 Summary of the effects of tree-crop integration on soil water balance compared with a sole crop (Ong 2001).

Water balance component	Change (% of rainfall)	
	Semi-arid climate	Humid tropic climate
Interception loss	+ 10%	+ 10 to 50%
Runoff	decrease	decrease
Soil water	decrease	decrease
Soil evaporation	- 10%	- 5%
Transpiration	increase	Increase
Drainage	decrease	decrease

2.5 Conclusions

Willow and poplar planted on hilly pastures for soil conservation purposes also provide palatable and nutritious fodder to livestock, during dry summers. Previous studies have shown that pastures during dry summers have lower nutritive value than willow and poplar foliage (leaf + thin stem). This indicates that establishment of willow and poplar trees will enhance food supply to livestock during periods when pasture production is low and of poor quality. This review highlighted important factors that influence establishment of willow and poplar such as climate, soil conditions, planting distance, planting material and weed control. Planting materials influence tree survival and eventually biomass production. Long stem cuttings planted vertically have higher shoot DM production. However, there is lack of information on optimum stem diameters for vertical planting and optimum stem lengths for horizontal planting. It is important to obtain reliable information on these aspects for successful establishment and production of willow and poplar in fodder blocks.

In agroforestry systems, knowledge of ways to reduce above- and below-ground competition is important to ensure successful establishment and higher shoot DM production. Competition between trees and pasture for soil water, particularly at soil depths of 0-150 mm and 0-300 mm, may influence tree water use, and consequently influence survival and shoot DM production. Thus, there is a need for simple and low cost understorey pasture management techniques and a knowledge and understanding of their effects on shoot DM production. These will provide the basis for formulating practical management recommendations for willow/poplar-pasture systems.

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3 Growth and yield of willow (*Salix* spp.), as influenced by clone and understorey pasture management in a willow-pasture agroforestry system

CONTENT

3.1 Introduction

Lack of forage particularly during dry summers is a serious problem in New Zealand. This can be partly addressed by using willow as a supplementary fodder. Willow is considered to be good not only for fodder (Kemp *et al*. 2001) but also for conserving soil (Cameron 2003; Anon 2005). The good palatability and nutritional value of fodder willow (Kemp *et al*. 2001), which is similar to, or often higher than pasture during drought (McCabe & Barry 1988), has encouraged farmers to use tree fodder as an additional source of animal feed during dry summers.

Resource competition between trees and understorey pasture is the most important factor that limits tree-pasture/crop growth. Previous research showed pasture production was reduced under poplar-pasture agroforestry (Wall e*t al*. 1997; Guevara-Escobar 1999). However annual pasture production estimates under a willow-pasture system in Wairarapa, New Zealand have increased because of the reduction in soil loss as result of tree planting (Cameron 2003).

During the first year of tree establishment in an agroforestry system, competition from understorey pasture for nutrients, light, and water can adversely affect tree survival and growth. According to Chang *et al*. (2003), growth (height and diameter) of radiata pine (*Pinus radiata*) was affected by understorey pasture competition in a silvopastoral system in New Zealand. A similar result was also obtained in USA by Delate *et al*. (2005), who found ground cover management influenced tree survival and tree growth (height and diameter) of silver maple and poplar clones 'Crandon' and 'Eugenei'. However, little research has been conducted on the effect of understorey pasture on tree growth of willow, particularly when it is managed in various ways. Herbicide applications have proven effective in controlling weeds, but they may also kill available pasture that can otherwise be utilised by animals. To determine best pasture management that can reduce competition, and increase animal fodder supply, an experiment was conducted at Massey University's experimental farm Moginie from December 2002 to April 2003.

In New Zealand, most agroforestry studies have focused on radiata pine (*Pinus radiata*) (Chang & Mead 2003) and poplar (*Populus* spp.) (Guevara-Escobar 1999) integrated with pasture. Information on willow-pasture intercrops is lacking, especially in regard to competition effects on willow growth and production. The main aim of this study was to examine the effect of understorey pasture management on survival, growth and shoot production of willow under willow/pasture systems.

3.2 Materials and methods

3.2.1 Experimental site

The experiment was conducted at the Pasture and Crop Unit, Moginie, Massey University, on a Tokomaru silt loam with aeric fragiaqualf (gleyed yellow-grey earth). The site is at 175 ^{o} 37 E longitude, 40 ^{o} 21 S latitude, and 30 m above sea level. Rainfall and temperature data (Figures 3.3 and 3.4) during the growing season were collected at AgResearch Grasslands, Palmerston North, 2.5 km from the experimental site.

The experimental site was prepared by eliminating existing pasture using glyphosate under the trade name of Roundup Renew XTRA at 2.25 l/ha (490 g glyphosate/l) on 1 August 2002. No weed control was conducted from planting till 19 December 2002.

3.2.2 Experimental treatments and design

Willow stem cuttings were planted on 5 September 2002 for the purpose of a grazing trial. However, the grazing trial did not materialize and those trees were available for this experiment. The trees were established using stem cuttings ranging from 10 to 40 mm diameter and they were 600 mm long. The cuttings were planted at 1.2 m x 1.2 m spacing (6944 trees/ha). Tree characteristics are described in Section 2.5.2 of chapter 2.

The treatments were:

(i) Two willow clones: a) 'Tangoio' (*Salix matsudana* x *alba*) (T)

b) 'Kinuyanagi' (*Salix kinuyanagi*) (K)

(ii) Three pasture managements:

a) Control (W1) - no weed control.

b) Herbicide (W2) - sprayed with Gallant NF at 3 l/ha (0.25 kg a.i. ha^{-1} haloxyfop (R-Isomer) and 0.87 kg a.i. ha^{-1} diethylene glycol) on 19 December 2002.

c) Mown monthly (W3) - cut at 2.5 cm above ground.

The understorey pasture treatments were started on 19 December, 2002. The six factorial treatments were arranged in three Randomised Complete Blocks (Figure 3.1) and each plot was 9.6 m x 10.8 m (72 trees/plot).

3.2.3 Tree measurements

3.2.3.1 Tree survival

Tree survival was surveyed initially on 19 December, 2002, 3.5 months after field planting. The survival rate of clones 'Kinuyangi' and 'Tangoio' was 99.4 and 99.5%, respectively. Tree survival surveys were also conducted on 6 January and 30 March, 2003 to determine the effect of pasture management on willow survival.

3.2.3.2 Tree growth

Willow growth (extension of height, shoot length, shoot diameter) were measured from December 2002 to March 2003. Canopy diameter extension (inter- and in-row canopy) was also measured at the same periods. Shoot growth was determined based on the difference in height, shoot length, shoot diameter and canopy diameter between measurement dates at monthly interval.

Canopy diameter is the maximum area covered by extended branch growth between and within rows.

The three longest shoots per tree were measured for shoot length and shoot diameter. Shoot diameter was measured using Vernier callipers. Shoot number per tree was also recorded monthly. The number of shoots per tree on 18 December 2002, before the experiment commenced, was 11.2 and 10.9 for willow clone 'Tangoio' and 'Kinuyanagi', respectively. Only the green parts of the tree were measured for tree height extension and canopy diameter extension. For better representation of the sample, 12 trees were selected randomly across the plot. The same trees were measured monthly from December 2002 to March 2003.

3.2.3.3 Willow biomass

Three willows per treatment (total of 18 trees), were harvested on 6 April 2003, before leaf fall in autumn, to compare the effects of pasture management on willow production. Fresh willow was divided into edible (leaf + stem ≤ 5 mm diameter) and non-edible (stem > 5 mm diameter) (Kemp *et al.* 2003) and oven-dried for at least 48 hours at 80 ^{o}C to determine dry matter (DM).

3.2.3.4 Understorey herbage mass

Herbage mass of pasture under spaced willows was harvested monthly before mowing. All material was washed before being oven dried. Four samples per plot were harvested randomly by cutting the pasture within 0.1 m^2 quadrats to ground level. The willow and pasture samples were oven dried at 80^{o}C for at least 24 hours to determine DM.

3.2.3.5 Soil water content

Soil water content (SWC) was measured monthly using Time Domain Reflectometry (TDR) (Parchomchuki *et al.* 1997), starting on 20 February 2003. A total of 144 sets (3 pasture managements x 2 clones x 2 soil depths x 4 trees/plot x 3 replicates) of permanent TDR probes were installed at 150 mm

and 300 mm depths. TDR probes were inserted vertically in each willow-pasture treatment plot, approximately 10 cm from the base of a tree. Four trees per plot were selected randomly. Irrigation was applied once every 30 days from 1 February to 31 March, 2003 due to drought season. The quantity of irrigation applied was 30 ml^3/hour for 12 hours (360 ml^3) or 19 mm per day. The volume of irrigation was measured using plastic containers (16 cm x 12 cm x 7 cm).

3.2.4 Statistical analysis

All data were analysed by Analysis of Variance (ANOVA), with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS 2001), and mean separation was conducted using the Least Significance Difference test at the 5% level. Repeated measures Analysis of Variance was conducted on tree survival to determine the effect of time on tree survival. Regression analyses were conducted to determine the relationship between total shoot length extension (shoot length extension x shoot number) and shoot volume (shoot length extension x shoot diameter) on total shoot DM. Data for tree survival and SWC were transformed (arcsin or log) with no significant differences being detected; thus the original measurement scales were used.

Figure 3.1 Treatment layout in randomised complete block design.

Block 1	Block 2	Block 3
KW3	TW2	KW1
KW1	KW1	TW3
TW3	TW1	KW2
KW2	TW3	TW2
TW1	KW3	TW1
TW2	KW2	KW3

Note:

Clone: T – Tangoio K – Kinuyanagi

Pasture management:

i. Control - no weed control (W1)
ii. Spray with Gallant NF for grass control (19 December 2002) (W2).
iii. Mown monthly (W3)

3.3 Results

3.3.1 Rainfall and temperature

Rainfall during the experiment (August 2002 to April 2003) ranged from 19.8 mm to 99.4 mm per month with a mean of 53.7 mm/month (Figure 3.2). January, February and March 2003 were the driest months with mean monthly rainfalls of 19.8, 23.4 and 26.8 mm, respectively. This was much lower than 2001 with means for rainfall of 73.6, 102.0 and 69.2 mm/month, respectively.

Mean temperature during the experiment (2002/2003) was 13.1 °C which was lower than the previous year's (2001/2002) which was 15.2 °C. The mean temperature during the experiment ranged from 8.2 to 14.4 °C compared to 12.6 to 17.7 °C in the previous year (Figure 3.3).

Figure 3.2 Rainfall in Palmerston North in 2001-2002 and 2002-2003.

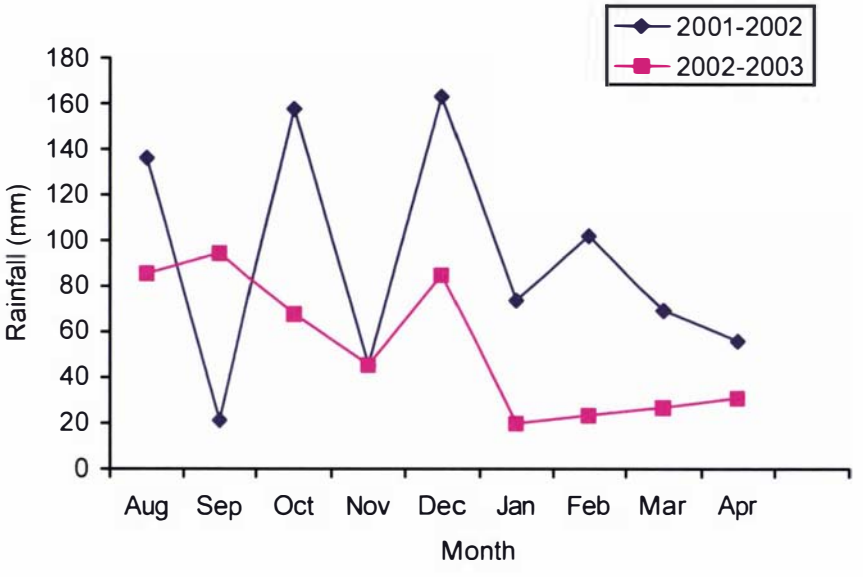
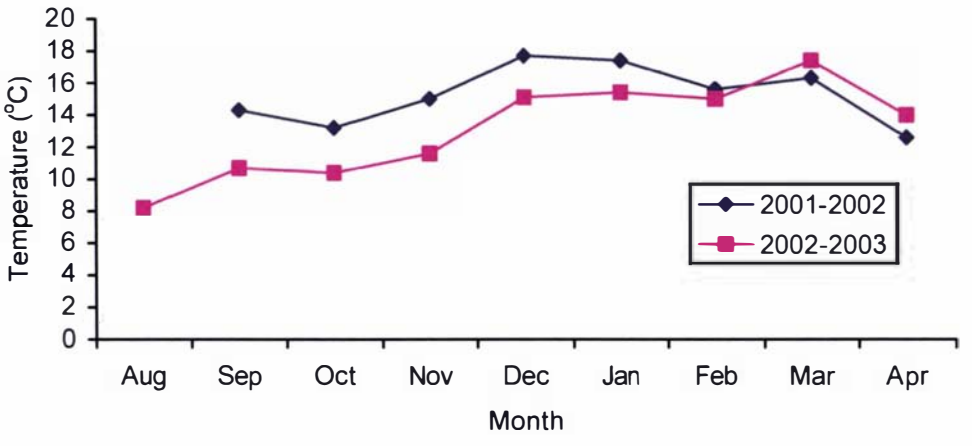


Figure 3.3 Mean air temperature in Palmerston North in 2001-2002 and 2002-2003.



3.3.2 Productivity of variously managed pasture beneath spaced willows

There was no significant interaction ($P > 0.05$) between clone and pasture management, except in February 2003 (Table 3.1).

Pasture management had a significant effect ($P = 0.0001$) on herbage mass. For example, in January 2003, control (no weed control) treatment had the highest herbage mass (7637 kg DM/ha) compared with the herbicide and mowing treatments (5997kg/ha and 3218 kg/ha, respectively). A similar trend was observed in February 2003. In March 2003, the control and herbicide treatments produced similar herbage masses that were greater than for the mown treatment of 8067 kg/ha = 6410 kg/ha > 1212 kg/ha, respectively (Table 3.1). There was no significant effect between clones on herbage mass.

Table 3.1 Herbage mass of various managed pasture beneath spaced willows.

Pasture management	Clone	Herbage mass (kg DM/ha.) 2003		
		Jan	Feb	Mar
Control	Kinuyanagi	7773	9360	9300
	Tangoio	7500	6847	6833
Herbicide	Kinuyanagi	5563	4803	6100
	Tangoio	6430	5317	6720
Mown	Kinuyanagi	2093	1667	1057
	Tangoio	1783	1300	1367
SEM (C*PM)		642	418	1030
Variable:			Probability	
Clone (C)		0.6556	0.1134	0.7278
Pasture-management (PM)		**0.0001**	**0.0001**	**0.0031**
C*PM		0.6775	**0.0085**	0.2367

SEM – Standard error of means

3.3.3 Soil water content

3.3.3.1 0-150 mm soil depth.

Soil water content (SWC) was affected ($P < 0.05$) by the interaction of clone and pasture management in March 2003 (Table 3.2). However there was no interaction between clone and pasture management on SWC in the other months. 'Kinuyanagi' had higher SWC in the mown treatment than the herbicide and control treatments in March, with means of 32% > 29% = 27%, respectively. In contrast, all pasture management treatments beneath 'Tangoio' had similar SWC.

Pasture management had a significant effect on SWC in April 2003 (Table 3.2) with mown pasture having significantly higher SWC (38%) than the control and herbicide treatments (34 % and 32 %, respectively). However, there was no significant effect of pasture management on SWC in February and March 2003. 'Kinuyanagi' had higher SWC than 'Tangoio' in March (29% vs 27%) and April 2003 (36 % vs 33 %).

Table 3.2 Effect of pasture management and willow clone on volumetric soil water content (%) at 0-150 mm depth.

Clone	Pasture management	Soil water content (%)		
		2003		
		Feb	Mar	Apr
Kinuyanagi	Control	23.4	27.2	34.7
Kinuyanagi	Herbicide	22.4	29.4	34.4
Kinuyanagi	Mown	26.9	31.5	39.5
Tangoio	Control	25.9	28.4	33.1
Tangoio	Herbicide	23.9	26.7	29.2
Tangoio	Mown	20.8	25.7	36.1
SEM (C*PM)		2.23	1.31	1.5
Variable:			Probability	
Clone (C)		0.7005	**0.0265**	**0.0069**
Pasture-management (PM)		0.8156	0.8141	**0.0006**
C*PM		0.1167	**0.0341**	0.4776

3.3.3.2 0-300 mm soil depth.

There was an interaction effect (P <0.0142) between clone and pasture management on SWC in March 2003 (Table 3.3) but not in the other months. Higher SWC was found in the mown and herbicide treatments than control for 'Kinuyanagi' (31.1 % = 31.0 % > 26.4 %, respectively) in March 2003. However, all pasture management treatments beneath 'Tangoio' had similar SWC.

There were significant differences between clone (March and April, 2003) and pasture management (April, 2003) on SWC (Table 3.3). 'Kinuyanagi' had higher SWC than 'Tangoio' in March (29 % vs 26 %) and April, 2003 (34 % vs 31 %). Pasture management had no effect on SWC except in April when mown treatment had higher SWC than the control and herbicide treatments with means of 35 % > 32% = 31%, respectively.

Table 3.3 Effect of pasture management and willow clone on volumetric soil water content (%) at 0-300 mm depth.

Clone	Pasture management	Soil water content (%)		
		2003		
		Feb	Mar	Apr
Kinuyanagi	Control	24.9	26.4	32.9
Kinuyanagi	Herbicide	23.1	30.6	33.5
Kinuyanagi	Mown	27.5	31.1	36.8
Tangoio	Control	27.3	27.6	32.0
Tangoio	Herbicide	24.4	26.2	27.8
Tangoio	Mown	23.4	25.4	33.9
SEM (C*PM)		2.1	1.2	1.3
Variable:			Probability	
Clone (C)		0.9196	**0.0036**	**0.0033**
Pasture-management (PM)		0.4845	0.4677	**0.0021**
C*PM		0.2530	**0.0142**	0.1698

3.3.4 Survival of willow trees in a willow-pasture agroforestry system with various pasture managements.

Tree survival was not affected by the interaction of clone and pasture management on 6 January and 30 March 2003 (Table 3.4).

Pasture management affected tree survival ($P < 0.05$) on 6 January 2003 (Table 3.4) with the mowing and herbicide treatments having higher tree survival than the control treatment, with means of 96.6% = 86% > 77%, respectively (Table 3.4).

On 30 March 2003 there was no significant effect between clone and pasture management treatments on tree survival (Table 3.4).

Overall, tree survival on 6 January 2003 (86.6%) was higher ($p < 0.03$) than on 30 March 2003 (75.6%)(Table 3.4).

Table 3.4 Willow tree survival (%) in a willow-pasture intercrop at three levels of pasture management.

Clone	Pasture management	Tree survival (%) 2003	
		6-Jan	30-Mar
Kinuyanagi	Control	85.2	69.4
Kinuyanagi	Herbicide	89.8	62.9
Kinuyanagi	Mown	97.7	81.0
Tangoio	Control	75.5	74.5
Tangoio	Herbicide	82.4	75.9
Tangoio	Mown	95.5	90.3
Mean		86.6	75.6
SEM (C*PM)		5.8	10.2
Variable:		Probability	
Clone (C)		0.101	0.173
Pasture-management (PM)		**0.023**	0.278
C*PM		0.502	0.967

3.3.5 Growth of two willow clones with three understorey pasture managements

3.3.5.1 Effect of pasture management on willow height extension

There was significant interaction between clone and pasture management on tree height extension from 20 December 2002 to 19 January 2003 (Table 3.5). No interaction was found for the other observation dates.

Pasture management had a significant effect ($P < 0.05$) on tree height at all times. For example, from 20 January to 19 February 2003, herbicide and mown treatments had significantly higher height extension than the control with means of 3.8 cm/month = 1.7 cm/month > -0.1 cm/month, respectively. A similar pattern was observed for mean overall height extension with herbicide and mown treatments showing higher extension than the control (5.3 cm/month = 4.6 cm/month > 2.3 cm/month, respectively).

Table 3.5 Effect of pasture management and clone on willow height extension.

Clone	Pasture management	Height extension rate (cm/month)			
		2002/2003			
		20 Dec - 19 Jan	20 Jan - 19 Feb	20 Feb - 19 Mar	Overall mean
Kinuyanagi	Control	4.5	-1.0	-0.3	1.4
Kinuyanagi	Herbicide	11.2	2.5	3.2	5.8
Kinuyanagi	Mown	6.5	2.6	2.1	3.9
Tangoio	Control	6.7	0.8	1.2	3.3
Tangoio	Herbicide	4.2	5.4	4.3	4.6
Tangoio	Mown	9.3	0.9	5.0	5.1
SEM (C*PM)		1	1.4	1.2	0.74
Variable:		Probability			
Clone (C)		0.4559	0.4783	0.0524	0.3306
Pasture-management (PM)		**0.0221**	**0.0257**	**0.0112**	**0.0004**
C*PM		**0.0001**	0.2583	0.7281	0.0703

Note: Negative value indicates shoot death during drought season.

3.3.5.2 Willow shoot number.

Shoot number was not affected by the interaction of clone and pasture management at each measurement date (Table 3.6).

Pasture management had a significant effect ($P < 0.05$) on shoot number in February and March 2003 (Table 3.6). For example, in March, mown and herbicide treatments produced more shoots than the control (6.6 = 6.1 > 5.1, respectively). A similar result was observed for the overall mean of shoot number (Table 3.6). 'Tangoio' produced greater ($P < 0.05$) overall mean shoot number than 'Kinuyanagi' (7.1 vs 6.3) (Table 3.6).

Table 3.6 Effect of pasture management and clone on willow shoot number.

Clone	Pasture management	Shoot number			
		2003			Overall
		19 Jan	19 Feb	19 Mar	mean
Kinuyanagi	Control	7.1	4.5	4.3	5.5
Kinuyanagi	Herbicide	6.9	6.2	5.9	6.3
Kinuyanagi	Mown	8.0	7.2	6.5	7.3
Tangoio	Control	7.6	6.3	6.0	6.7
Tangoio	Herbicide	8.0	7.0	6.4	7.2
Tangoio	Mown	8.4	6.7	6.7	7.3
SEM (C*PM)		0.5	0.5	0.5	0.3
Variable:			Probability		
Clone (C)		0.0955	0.0854	0.0635	**0.0044**
Pasture-management (PM)		0.2302	**0.0103**	**0.0142**	**0.0008**
C*PM		0.7494	0.0817	0.2442	0.1189

3.3.5.3 Willow shoot length extension

Shoot length extension was affected by the interaction of clone and pasture management from 21 December 2002 to 20 January 2003 (Table 3.7). However, there was no interaction on the other observations dates.

Pasture management ($P < 0.05$) and clone ($P < 0.05$) had significant effects on shoot length extension during all periods. For example from 21 February to 20 March 2003, Kinuyanagi produced greater shoot length extension than Tangoio (3.7 cm/month vs 1.2 cm/month). Herbicide and mown treatments produced greater shoot length extension than the control treatment with means of 3.1 cm/month = 2.6 cm/month > 1.6 cm/month, respectively (Table 3.7). A similar result was observed on overall mean shoot length extension.

Table 3.7 Effect of pasture management and clone on willow shoot length extension.

Clone	Pasture management	Shoot length extension (cm/month)			
		2002/2003			
		21 Dec-20 Jan	21 Jan-20 Feb	21 Feb-20 Mar	Overall mean
Kinuyanagi	Control	1.5	1.9	2.7	1.9
Kinuyanagi	Herbicide	2.3	3.3	4.5	3.3
Kinuyanagi	Mown	3.4	2.8	3.5	3.2
Tangoio	Control	1.9	-2.7	0.8	-0.01
Tangoio	Herbicide	1.2	1.1	1.3	1.2
Tangoio	Mown	5.3	-0.8	1.5	2.2
SEM (C*PM)		0.4	0.8	0.5	0.3
Variable:			Probability		
Clone (C)		**0.0414**	**0.0001**	**0.0001**	**0.0001**
Pasture-management (PM)		**0.0001**	**0.0039**	**0.0347**	**0.0001**
C*PM		**0.0004**	0.3121	0.2863	0.1988

Note: Negative value indicates shoot die-back during drought season.

3.3.5.4 Willow shoot diameter extension

There were no significant ($P > 0.05$) differences in shoot diameter extension between pasture managements, clones or their interaction throughout the experiment. The only exception was found on 21 December 2002 - 20 January 2003 for clone (Table 3.8) when 'Tangoio' willow had greater ($P < 0.05$) shoot diameter (2.5 vs 2.0 mm) than 'Kinuyanagi' willow.

Table 3.8 Effect of pasture management and clone on willow shoot diameter extension.

Clone	Pasture management	Shoot diameter growth (mm/month)			
		2002/2003			Overall mean
		21 Dec - 20-Jan	21 Jan - 20-Feb	21 Feb - 20 Mar	
Kinuyanagi	Control	1.9	0.8	0.4	1.2
Kinuyanagi	Herbicide	2.0	1.4	0.4	1.3
Kinuyanagi	Mown	2.3	0.8	0.7	1.3
Tangoio	Control	2.4	1.0	0.2	1.2
Tangoio	Herbicide	2.5	0.8	0.4	1.3
Tangoio	Mown	2.5	0.7	0.5	1.3
SEM (C*PM)		0.3	0.2	0.1	0.1
Variable:		Probability			
Clone (C)		**0.0497**	0.1859	0.1978	0.6955
Pasture-management (PM)		0.6021	0.0551	0.074	0.7417
C*PM		0.7242	0.0587	0.684	0.9952

3.3.5.5 Willow canopy diameter extension

3.3.5.5.1 In-row canopy diameter extension

In-row canopy diameter extension was affected by the interaction of clone and pasture management on 20 January - 19 February 2003 (Table 3.9). 'Kinuyanagi' produced significantly greater in-row canopy diameter extension from the mown treatment than the herbicide and control treatments with means of 0.6 cm/month > -1.5 cm/month > -6.0 cm/month, respectively. However 'Tangoio' produced greater in-row canopy diameter extension from the herbicide treatment than the control and mown treatments (2.1 cm/month > -1.8 cm/month > -3.3 cm/month, respectively). There were no interactions between clone and pasture management on the other observations dates.

Pasture management had a significant effect on in-row canopy diameter extension on 20 December 2002 - 19 January 2003, and 20 January - 19 February 2003. For example, the herbicide and mown treatments produced greater in-row canopy diameter extension than control treatment with means of 0.2 cm/month = -1.5 cm/month > -4.0 cm/month, respectively. A significant effect ($P < 0.05$) was found for clone on in-row canopy diameter extension on 20 December 2002 - 19 January 2003 when 'Kinuyanagi' produced greater in-row canopy diameter extension than 'Tangoio' (2.9 cm/month vs 0.02

cm/month). However no difference between clones was detected during later periods.

Table 3.9 Effect of pasture management and clone on in-row canopy diameter extension.

Clone	Pasture management	In-row canopy diameter extension (cm/month)			
		2002/2003			
		20 Dec - 19 Jan	20 Jan - 19 Feb	20 Feb - 19 Mar	Overall mean
Kinuyanagi	Control	3.2	-6.0	2.8	0.2
Kinuyanagi	Herbicide	2.2	-1.5	0.8	0.6
Kinuyanagi	Mown	3.3	0.6	1.9	2.0
Tangoio	Control	-1.5	-1.8	1.5	-0.8
Tangoio	Herbicide	-0.6	2.1	3.5	1.6
Tangoio	Mown	1.8	-3.3	4.6	1.0
SEM (C*PM)		1.7	1.1	1.2	0.9
Variable:		Probability			
Clone (C)		**0.0325**	0.2164	0.1073	0.7335
Pasture-management (PM)		**0.0440**	**0.0010**	0.4800	0.1117
C*PM		0.4018	**0.0002**	0.1804	0.4582

Note: Negative value indicates shoot die-back during drought season.

3.3.5.5.2 Inter-row canopy diameter extension

There was significant interaction ($P < 0.05$) between clone and pasture management on inter-row canopy diameter extension on 20 December 2002-January 2003 and 20 January-19 February 2003, and overall mean (Table 3.10). For example from 20 December 2002-19 January 2003, 'Tangoio' produced greater inter-row canopy diameter extension from the herbicide treatment than the mown and control treatments (19 cm/month > 15 cm/month= 14 cm/month, respectively). However, this contrasted with results for 'Kinuyanagi' where the mown and control treatments produced greater inter-row canopy diameter extension than the herbicide treatment with means of 12.3 cm/month =14.2 cm/month > 7.6 cm/month, respectively.

There was no significant effect of pasture management on inter-row canopy diameter extension except during 20 January - 19 February 2003 when the mown and herbicide treatments produced greater inter-row canopy diameter extension than control in the order -1.0 cm/month = -1.4 cm/month > -4.7

cm/month, respectively. 'Tangoio' produced greater inter-row canopy extension than 'Kinuyanagi' on 20 December 2002 - 19 January 2003. However, no difference was found on the other observations dates.

Table 3.10 Effect of pasture management and clone on inter-row canopy diameter extension.

Clone	Pasture management	Inter-row canopy diameter extension (cm/month)			
		2003			Overall mean
		20 Dec - 19 Jan	20 Jan - 19-Feb	20 Feb - 19-Mar	
Kinuyanagi	Control	14.2	-7.4	3.3	4.1
Kinuyanagi	Herbicide	7.6	-2.0	1.2	2.4
Kinuyanagi	Mown	12.3	1.2	2.0	5.5
Tangoio	Control	13.8	-1.6	1.7	5.4
Tangoio	Herbicide	19.0	-0.8	3.0	7.8
Tangoio	Mown	14.9	-2.8	2.7	5.1
SEM (C*PM)		1.7	1.5	1.3	1.2
Variable:		Probability			
Clone (C)		**0.001**	0.397	0.644	**0.028**
Pasture-management (PM)		0.897	**0.047**	0.888	0.961
C*PM		**0.001**	**0.002**	0.561	0.032

Note: Negative value indicates shoot die-back during drought season.

3.3.6 Effect of pasture management and clone on willow biomass production

There was no significant interaction between clone and pasture management on edible, non-edible and total shoot DM (Table 3.11).

Pasture management had significant effects on edible (P=0.0003), non-edible (P=0.005) and total shoot DM (P=0.001)(Table 3.11). The mown treatment produced higher edible DM (17.8 g DM/tree) than the herbicide (12.5 g DM/tree) and control treatments (12.4 g Dm/tree). Similar results were found for non-edible (20.7 g DM/tree > 14.9 g DM/tree = 14.1 g DM/tree, respectively) and total shoot DM (38.4 g DM/tree > 27.3 g DM/tree = 26.4 g DM/tree, respectively).

Clone had a significant effect on edible DM (P=0.0001) and total shoot DM (P=0.0001). 'Kinuyanagi' produced greater edible DM (20.2 vs 8.2 g DM/ tree) and total shoot DM (38.3 g DM/tree vs 23.1 g DM/tree) than 'Tangoio'. However, no significant effect was found on non-edible DM.

Table 3.11 The effect of pasture management and clone on willow biomass.

Clone	Pasture Management	Willow dry matter (g DM/tree)		
		Edible DM	Non edible DM	Total shoot DM
Kinuyanagi	Control	18.8	17.1	35.9
Kinuyanagi	Herbicide	18.3	17.0	35.2
Kinuyanagi	Mown	23.7	20.2	43.9
Tangoio	Control	5.9	11.0	16.9
Tangoio	Herbicide	6.8	12.8	19.5
Tangoio	Mown	11.8	21.2	33.0
SEM (C*PM)		1.4	2.2	3.5
Significance			Probability	
Clone (C)		**0.0001**	0.0848	**0.0001**
Pasture-management (PM)		**0.0003**	**0.0057**	**0.0013**
C*PM		0.8875	0.2492	0.5110

3.3.7 Relationships between yield components (total shoot extension and shoot volume) on total shoot DM.

There was a linear relationship (R^2 = 0.76, P < 0.026) between total shoot length extension (shoot length extension x shoot number) and total shoot DM (Figure 3.4). A linear relationship (R^2 = 0.72, P < 0.038) was also found between shoot volume extension (shoot length extension x shoot diameter) and total shoot DM (Figure 3.5). However in the drought conditions, negative shoot extension was found.

Figure 3.4 Relationship between total shoot length extension (shoot length extension x shoot number) and shoot dry matter.

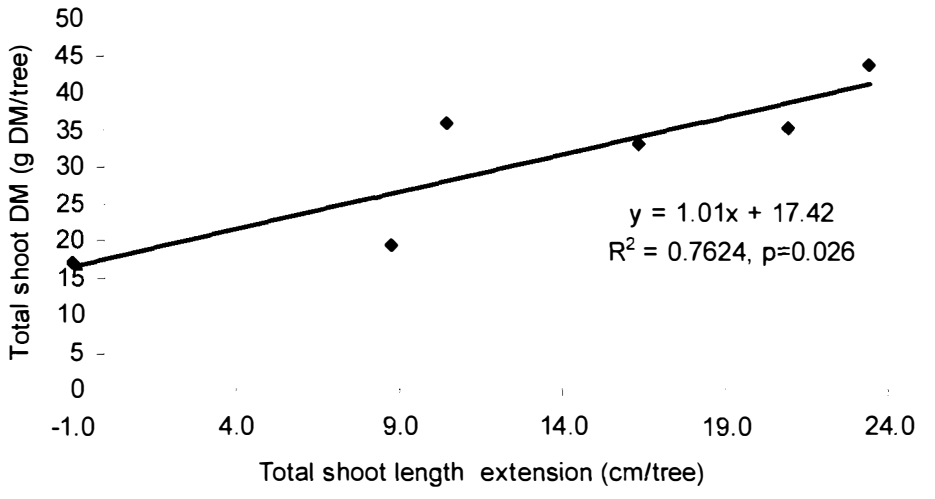
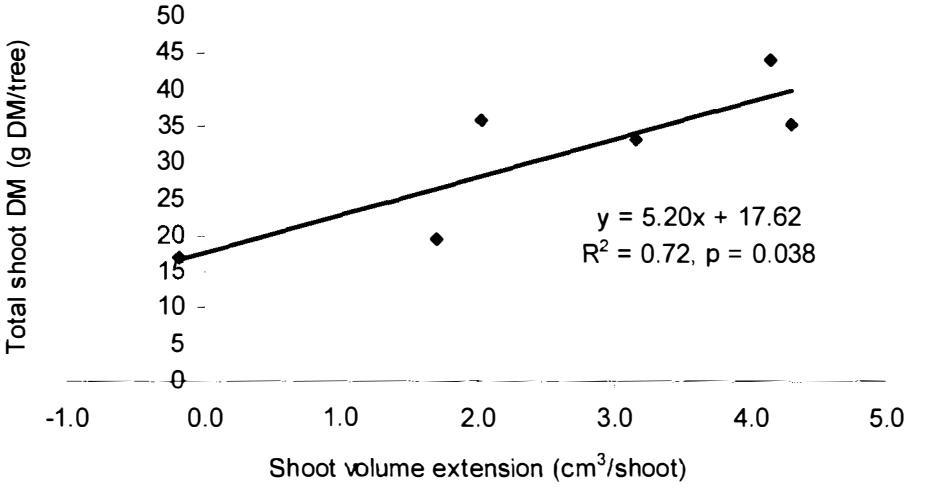


Figure 3.5 Relationship between shoot volume extension (shoot length extension x shoot diameter) and total shoot dry matter.



3.4 Discussion

3.4.1 Tree survival, rainfall and soil water content.

The high survival of willow clones 'Kinuyanagi' and 'Tangoio' (means of 90.9% and 84.5%, respectively) on 6 January 2003, four months after field planting was assisted by the high rainfall from August to December 2002 (382 mm)(Figure 3.2). Lack of soil moisture during summer/autumn (February to March 2003) (Tables 3.2 and 3.3) probably contributed to the lower survival in March 2003 when survival ranged from 69.4% to 90.3% depending on pasture management (Table 3.4). Previous study found that lack of soil moisture and excessive weed growth are the main factors that limit willow establishment (Hathaway 1986a, b) and growth (Pezeshki *et al*. 1998; Schaff *et al*. 2003). Low survival of willow during drought summers might have been caused by low root production, but this was beyond the scope of this study. Therefore, further study is needed to establish the relationship between root production and tree survival.

Pasture managements using mowing and herbicide resulted in higher tree survival (6 January 2003) than no weed control (control treatment) under favourable weather conditions. The higher tree survival was probably because of less understorey competition in the mown and herbicide treatments. However, Conroy *et al*. (1991) found no effect of grazing treatment (understorey management) on willow survival. Under the dry conditions from 7 January to 31 March 2003 (Figure 3.3), pasture management had no effect on tree survival. Irrigation once a month was insufficient to prevent cuttings from dying.

It was observed that the willow foliage had severe shoot die-back, particularly clone 'Tangoio', and this was probably because of the water shortage during summer which contributed to vegetative growth. Higher water use by 'Tangoio' than 'Kinuyanagi' may explain why this clone was more sensitive during severe water stress. In a study by Tharakan *et al*. (2003) tree survival of several clones of willow ranged from 82.2 to 100% and mean total precipitation during the study was 500 mm. In the current study, total precipitation during the

experiment period was 487 mm, but summer mean precipitation ranged from only 19.8 to 26.8 mm/month, which caused many shoots to die.

The higher mean temperature in summer (15.5 ^{o}C) than in spring (11.2 ^{o}C), likely caused higher water losses through evapotranspiration and the soil was relatively firm in summer because of low soil water content. The low water availability caused high tree mortality.

3.4.2 Growth of willow in the presence of variously managed understorey pasture.

Mean pasture herbage mass was higher in the control (no weed control) treatment (7936 kg DM/ha), followed by the herbicide (5822 kg DM/ha) and mown treatments (1545 kg DM/ha) (Table 3.1). These results indicated that greatest competition occurred between willow and pasture in the control treatment, followed by the herbicide and mown treatments. Higher understorey herbage mass in the herbicide treatment than the mown treatment was possibly because the recommended herbicide dose was not sufficient to kill the understorey pasture entirely, which was growing excessively and vigorously at the time of application.

Willow growth (mean height extension, mean shoot number and mean shoot length extension) was improved more in the mown and herbicide treatments than the no weed control treatment. This may be because the reduced competition between willow and the understorey pasture enabled higher shoot growth. This was supported by Corey *et al.* (1998) who found poplar tree height and diameter were reduced by weed competition in plots where herbicide treatments did not provide adequate weed control, and in some of the weediest plots, poplar trees died due to weed competition. Mark *et al.* (2001) also found that tall, fast-growing weed species reduced growth of *Pinus radiata* by less than 10% when weeds were 50% of tree height and by about 30%, when the weeds were 75% of tree height. Negative growth during summer from 20 January to 19 March, 2003 was because of low rainfall and low SWC, resulting in severe water stress leading to shoot die-back.

Weather was also an important factor that influenced willow growth. Significant differences in the shoot growth were found between pasture management treatments during favourable weather conditions. For instance, willow shoot length extension was higher in the period 21 December 2002 - 20 January 2003 compared to 21 January - 20 February 2003. This may be due to the influence of rainfall on growth. Negative shoot length extension was found for clone 'Tangoio' in the period 21 January - 20 February 2003 when there was low soil water content, indicating that the clone was relatively sensitive to seasonal drought. Higher shoot length extension from clone 'Kinuyanagi' indicated that this clone was more drought-tolerant than 'Tangoio'. However this finding was in contrast to that of McCable *et al.* (1988) who found that clone 'Tangoio' was a drought-tolerant willow.

The general lack of interaction between clone and pasture management on tree survival and shoot growth (height extension, shoot number, shoot length extension and canopy diameter extension) suggests that the response of willow clones to understorey management was similar.

3.4.3 Effect of pasture management on willow biomass production

Results clearly show that edible and total shoot DM were influenced by clone ($P < 0.0001$), although they were also affected by pasture management ($P < 0.05$). 'Kinuyanagi' had greater edible DM and total shoot DM than 'Tangoio'. This was probably because 'Kinuyanagi' had higher shoot growth (mean height extension, mean shoot length extension), which resulted in higher total shoot DM. The higher yield of 'Kinuyanagi' compared to 'Tangoio' was in agreement with results reported by Douglas *et al.* (1996) who found the same trend for edible DM (1.84 vs. 1.2 t/ha) and total shoot DM (5.2 vs. 4.3 t/ha). Another factor that reduced biomass production of 'Tangoio' was the attack on the foliage by willow sawfly (*Nematus oligospilus*), although harvests were conducted in the early stage of infestation. Estimates of edible DM and total shoot DM were lower than found by Douglas *et al.* (1996), possibly because low rainfall and low soil water content during summer (Figure 3.2) caused slow growth and low total biomass production.

Similar edible and total shoot DM of willow in the herbicide and control (no weed control) treatments suggests that the herbicide treatment, with one application per season, was not effective in decreasing competition from the pasture understorey. In hindsight, the herbicide should have been applied earlier and more often. This suggests that spraying of herbicide should be conducted in November to ensure that responses to herbicide can be achieved without significant influence by other factors. From experience gained, it is suggested that understorey pasture should be sprayed at least twice to enable better growth and higher biomass production of willow.

There was a linear relationship between total shoot length extension and shoot volume extension on total shoot DM indicating that both parameters were important for willow biomass production. During drought conditions in summer 2003, shoot extension was negative, probably because of shoot die-back in response to plant water deficits, which caused low biomass production of willow.

3.5 Conclusions

The results indicated that pasture management is important in determining willow growth, survival and shoot DM production in willow-pasture agroforestry systems. The mown and herbicide treatments had higher tree survival than the control (no weed control) treatment (96.6% = 86% > 77%) on 6 January 2003, 120 days after planting. However, no significant differences in the tree survival were found between pasture management treatments on 30 March 2003 (200 days after planting), indicating severe dry conditions had a similar effect on all pasture management treatments.

Significantly higher mean growth (shoot number, and extension of height and shoot) was found for the mown and herbicide treatments than for the control treatment. Higher growth from the mown treatment resulted in higher edible and total shoot DM than from the herbicide and control treatments.

Clone selection also influenced biomass production. Higher edible DM and total shoot DM were found for clone 'Kinuyanagi' than 'Tangoio'. This was because

'Tangoio' was more sensitive to dry conditions whereas 'Kinuyanagi' showed relative resistance to dry weather situations.

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4 Effects of stem diameter and planting depth on survival and early growth of field-planted willow and poplar

CONTENT

4.1 Introduction

Willow and poplar are widely used multipurpose trees and shrubs with soil conservation, shelter, firewood, ornamental, medicinal, furniture and paper pulp uses, as well as being used for fodder in summer droughts. Like many tree species, willow (*Salix* spp.) and poplar (*Populus* spp.) are slow to establish in comparison to herbaceous species. Previous experience by the author in Manawatu New Zealand with the establishment of willow using unrooted stem cuttings in a fodder block showed that willow were very sensitive to unfavorable weather conditions especially for the first 12 months after field planting. Small plants were vulnerable to limited water supply and weed competition. Based on this experience, an experiment was designed to determine the planting size of stem cuttings that provided effective growth, biomass production and sustainable establishment of willow and poplar in a fodder block.

Stem cuttings have been used for field establishment of many tree species such as *Pinus radiata* (Anon 1995), willow (Douglas *et al.* 2003) and poplar (van Kraayenoord *et al.* 1986). Unrooted stem cuttings are often preferred for field establishment because they are inexpensive and easy to handle (Zsuffa 1992), and provide uniformity and conformity to the pure species (Newsholme 1992).

Poplar and willow can be established by vertically planting stem cuttings which are often 1.0-2.0 m long, with diameters of 15-25 mm and 20-40 mm, respectively (van Kraayenoord *et al.* 1986). Douglas et al. (2003) found that the total yield of willow planted as 2 m stem cuttings was higher than 1.1 m stem cuttings after 2.5 years of field planting. Nevertheless, there is negligible scientific research on the effect of stem diameter on willow and poplar establishment and biomass production. According to Douglas et al. (2003), experience from farmers and land managers has shown that burying one-quarter to one-third of the cutting length provides satisfactory plant survival and growth in a range of environments, however, there is little research to support this hypothesis.

Based on reviewed literature and experience, our hypothesis was that thick stem diameters give better plant establishment. To test this hypothesis, three cutting diameters and two planting depths were used.

The objectives of this paper are: (i) to determine the effect of three stem cutting diameters and two planting depths on plant survival, growth and biomass production of willow and poplar, and (ii) to determine the effect of three cutting diameters and two planting depths on root biomass of willow and poplar.

4.2 Materials and methods

4.2.1 Experimental site

The research was conducted at the Pasture and Crop Unit, Moginie, Massey University, Palmerston North (longitude 175 ^{o} 37' E, latitude 40 ^{o} 21' S, altitude 30 m above sea level), on a Tokomaru silt loam with aeric fragiaqualf (gleyed yellow-grey earth) from August 2003 to March 2004. Rainfall and temperature during the growing season were obtained from AgResearch Grasslands, Palmerston North, 2.5 km from the experimental site.

The sites were sprayed with Roundup Renew XTRA at 2.25 l/ha (490 g glyphosate/l) to suppress the existing pasture on 24 July 2003. When plants were covered by weeds, manual weeding using secateur was conducted on 23 October 2003 and 28 January 2004. Versatill, at 1.0 l/ha (300 g clopyralid/l) was sprayed with care between rows on 12 December 2003 to kill Scotch thistle (*Cirsium vulgare*) and Clustered dock (*Rumex conglomeratus* Murr). Orthene (195 g/l acephate plus 346 g/l ethylene glycol) was sprayed at 0.4 l/ha on 28 February 2004 to control willow sawfly (*Nematus oligospilus*).

4.2.2 Experimental treatments and design

Stem cuttings of one year old wood were planted on 6 August 2003 at 1.0 m x 1.0 m spacing (10,000 stems/ha). The site was ripped at 300 mm before planting. The planting material was collected from Greater Wellington Regional Council's Akura nursery, Masterton, on 4 July, 2003, and kept in a cool room for

30 days. All the planting material was soaked in water for 48 hours before planting. Factorial treatments were arranged in three randomized complete blocks and each experiment unit was 5 m x 5 m with 36 plants per plot with totals of 36 plots (3 stem diameters x 2 planting depths x 2 species x 3 replicates). Both willow and poplar were established from 600 mm long stem cuttings.

The treatments were:

1. Stem diameter: The three stem diameters were: (i) 10 mm (range 9-12 mm); (ii) 25 mm (range 20-30 mm); and iii) 35 mm (ranges 31-40 mm). The mean diameter of stem cuttings was measured at the mid-length of the stem.

2. Planting depth: either (i) 150 mm or (ii) 300 mm of the stem cutting was pushed into the soil.

3. Plant species: the species were (i) *Salix matsudana x alba* (willow clone 'Tangoio') and, ii) *Populus deltoides x nigra* (poplar clone 'Veronese').

4.2.3 Tree measurements

4.2.3.1 Tree survival

Tree survival was assessed on 9 December 2003 and 16 March 2004 to determine the effects of stem diameter on tree survival.

4.2.3.2 Tree growth performance

Growth of willow and poplar was measured monthly in terms of tree height, number of shoots, shoot length, shoot diameter and maximum canopy diameter (measured perpendicular to the original planting row). Eight trees were selected per plot for analysis.

4.2.3.3 Biomass of willow and poplar

4.2.3.3.1 Above-ground biomass

A total of 36 trees per harvest with 18 trees each from willow and poplar (1 tree per plot) were harvested using different trees each time on 6 January 2004 and 16 March 2004. Fresh material was divided into edible (leaf and stem < 5mm diameter) and non-edible (stem > 5 mm diameter) (Kemp *et al.* 2003), and the former material was oven-dried at 80 ^{o}C for 48 hours to determine edible dry matter (DM) and total shoot DM production. The non-edible component, with bigger stems, was oven-dried from 48 hours to 186 hours at 80 ^{o}C.

4.2.3.3.2 Below-ground biomass

Below-ground biomass measurement included root number, root length, root volume, root DM, percentage (%) of root DM and ratio of root length and root volume (R_{LV} ratio). The same trees that were used for above-ground biomass were used for below-ground biomass. Roots were excavated from a pit size of 0.5 m x 0.5 m x 0.4 m from the field trial area (Photo 4.1). Root volume was measured using a cylinder, sizes ranging from 10 cm^3 to 200 cm^3. Root volume was determined based on the difference in water level raised before and after

the root was immersed. Percentage of root DM (% RDM) was calculated as % RDM = (root DM/ root DM + shoot DM) * 100.

Photo 4.1 Harvesting poplar for above- and below-ground biomass study.

4.2.3.4 Soil water content

Site volumetric soil water content was measured monthly at 0-150 mm and 0-300 mm soil depths from October 2003 to March 2004 using Time Domain Reflectometry (TDR) (Parchomchuki *et al.* 1997). A total of twelve pairs of permanent TDR probes were inserted randomly in the experimental area, approximately 150 mm away from the base of a tree.

4.2.3.5 Statistical analysis.

All data were analysed by Analysis of Variance (ANOVA) with repeated measures, with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS 2001) and mean separation was achieved using the Least Significant Difference test at the 5% significance level. Regression analyses were conducted to determine the relationship between (i) root DM and edible DM and (ii) root DM and total DM at 225 DAP.

4.3 Results

4.3.1 Rainfall and temperature

The total rainfall during the growing season (2003/2004) was 886 mm (Figure 4.2), with rainfall during summer 78 mm in December, 2003, 92 mm in January 2004 and 299 mm in February 2004. The mean maximum and minimum temperatures during the growing season were 19 °C and 10 °C, respectively (Figure 4.1).

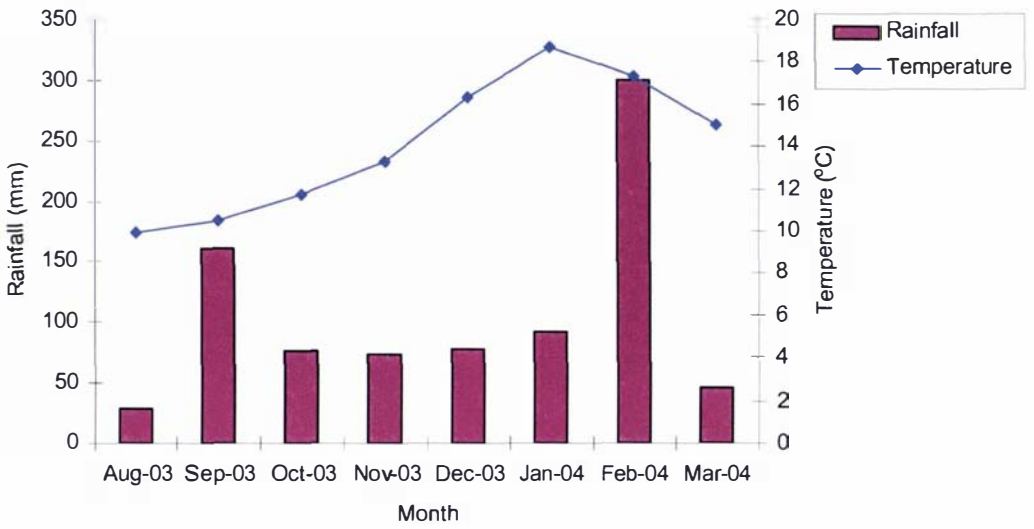

Figure 4.1 Mean rainfall and temperature at Palmerston North during the 2003/2004 growing season.

4.3.2 Soil water content

Soil water content (SWC) from 13 October 2003 to 15 March 2004 is presented in Figure 4.3. SWC at 0-150 mm soil depth, ranged from 27% to 43%, with a mean of 34%. During the three summer months, SWC was 31% (15 December 03), 33% (23 January 04) and 38% (25 February 04) (Figure 4.2).

SWC at 0-300 mm depth ranged from 27% to 37% with a mean of 30%. On 15 December 03, 23 January 04, and 25 February 04, SWC was 27%, 29% and 35%, respectively (Figure 4.2).

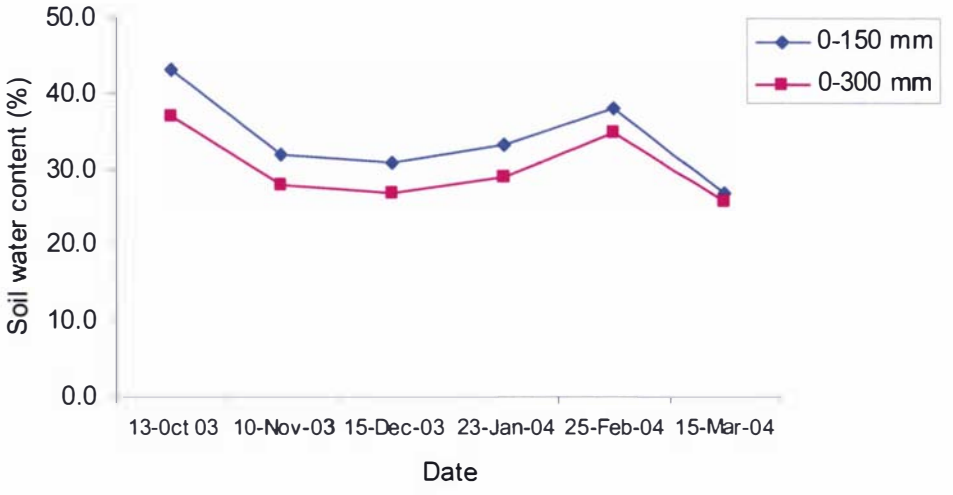

Figure 4.2 Volumetric soil water content (%) at 0-150 mm and 0-300 mm during the growing season at the experimental site.

4.3.3 Survival of stem cuttings

Stem diameter (P= 0.0001) and planting depth (P = 0.02) affected survival of stem cuttings 123 days after field planting (Table 4.1). There were no species or treatment interaction effects on tree survival. Survival rate was 99% for the 35 mm and 25 mm diameter stems, whereas survival rate for the 10 mm diameter stems was 93% (Table 4.1). Stem cuttings planted at 150 mm soil depth had greater survival than at 300 mm planting depth (98% vs 96%).

At 224 days after planting, there was a significant effect of stem diameter on survival (P = 0.0006). However, there were no significant species, depth or interaction effects on survival. Survival was higher for the 25 mm (99 %), and 35 mm (98%) than for 10 mm diameter stems (93%).

Table 4.1 Effects of stem diameter and planting depth on survival of willow and poplar trees established using 600 mm long stem cuttings.

Species	Stem diameter (mm)	Planting depth (mm)	Tree survival (%) Days after planting 123	224
Poplar	10	150	95	91
Poplar	10	300	94	93
Poplar	25	150	100	98
Poplar	25	300	99	99
Poplar	35	150	100	99
Poplar	35	300	98	96
Willow	10	150	95	95
Willow	10	300	92	92
Willow	25	150	100	100
Willow	25	300	98	98
Willow	35	150	100	100
Willow	35	300	99	98
SEM (S*P*D)			1.5	2.0
Variable:			Probability	
Species (S)			0.4933	0.3495
Stem diameter (P)			**0.0001**	**0.0006**
Planting depth (D)			**0.0225**	0.3265
S*P			0.5693	0.9329
S*D			0.4933	0.3175
P*D			0.4791	0.7569
S*P*D			0.5693	0.5721

SEM : standard error of the least square means

4.3.4 Effect of stem diameter and planting depth on plant growth

4.3.4.1 Shoot number

There were significant (P=0.0001) interactions between (i) species and stem diameter, and (ii) stem diameter and planting depth on shoot number (Table 4.2). There were no interactions between species, planting depth and stem diameter, and species and planting depth, except at 32 and 62 DAP and 32 DAP, respectively (Table 4.2). Willow produced higher shoot numbers from 35 mm diameter stems than 25 mm and 10 mm diameter stems. However, 10 mm poplar stem cuttings produced higher shoot numbers than 35 mm and 25 mm for the first 62 DAP. No significant effect was found for poplar on shoot number at later observation dates.

The main effects of species and stem diameter had a significant effect (P=0.0001) on shoot number (Table 4.2). For example, at 198 DAP willow produced greater shoot numbers than poplar (11 vs 6). Thick stems produced greater shoot numbers than thin stems (P= 0.0001). At 198 DAP, the thickest stem diameter, 35mm, produced greater shoot numbers (11) than 25 mm and 10 mm stems, with a mean of 8 and 5 shoots, respectively. A similar trend was found for other observation dates. No significant effect was observed for planting depth on shoot number except at 32 DAP when planting depth of 150 mm produced higher shoot number than those trees planted at 300 mm planting depth.

Table 4.2 Effects of stem diameter and planting depth of willow and poplar on shoot number.

Species	Stem diameter (mm)	Planting depth (mm)	Shoot number Days after planting 32	62	93	133	164	198
Poplar	10	150	5	6	6	6	6	6
Poplar	10	300	5	6	5	5	4	4
Poplar	25	150	2	2	4	5	5	5
Poplar	25	300	4	5	7	6	6	5
Poplar	35	150	5	6	7	7	7	7
Poplar	35	300	3	3	5	7	6	6
Willow	10	150	9	11	8	8	7	7
Willow	10	300	5	6	6	7	6	5
Willow	25	150	11	14	15	15	13	12
Willow	25	300	7	11	15	17	15	13
Willow	35	150	15	15	20	18	17	16
Willow	35	300	16	18	19	17	15	14
SEM (S*P*D)			0.8	0.9	1.0	0.8	0.7	0.7
Variable:			Probability					
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0433**	0.1346	0.5106	0.4636	0.2601	0.1208
S*P			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*D			**0.0241**	0.0614	0.2984	0.6512	0.9035	0.9066
P*D			0.1819	**0.0413**	**0.0176**	**0.0113**	**0.0098**	**0.0263**
S*P*D			**0.0006**	**0.0001**	0.4466	0.7530	0.4077	0.6290

4.3.4.2 Shoot length

There were significant (P= 0.0001) interactions between (i) species, stem diameter and planting depth, (ii) species and stem diameter, and (iii) stem diameter and planting depth on shoot length, but significant interactions between species and planting depth only occurred at 62 and 93 DAP (Table 4.3). For example at 198 DAP, 35 mm (151 cm vs 111 cm) and 25 mm (126 cm vs 92 cm) willow stem cuttings produced longer shoots than poplar, but shoots produced by 10 mm diameter stems of both species (66 cm vs 62 cm) were similar.

Willow produced longer shoots (P= 0.0001) than poplar. At 198 DAP, the mean shoot length of willow was 117 cm, whereas poplar shoot length was 88 cm. Willow also produced longer shoots at earlier observation dates. Thick stem cuttings produced longer shoots than thin stems ($P < 0.05$). For example at 198 DAP, 35 mm diameter stems produced longer shoots than 25 mm and 10 mm diameter stems with means of 134 cm, 110 cm and 64 cm, respectively. A similar trend was found for other dates of measurement. The effect of planting depth was significant for the first two measurement dates only (Table 4.3), when higher shoot length was found for 150 mm planting depth than 300 mm depth (9 cm vs 8 cm and 24 cm vs 21 cm at 62 and 93 DAP, respectively).

Table 4.3 Effects of stem diameter and planting depth of willow and poplar on shoot length.

Species	Stem diameter (mm)	Planting depth (mm)	Shoot length (cm) Days after planting 62	93	133	164	198
Poplar:							
Poplar	10	150	4	10	34	48	76
Poplar	10	300	7	8	22	32	48
Poplar	25	150	3	13	45	65	90
Poplar	25	300	3	11	45	66	94
Poplar	35	150	5	19	55	75	102
Poplar	35	300	5	19	65	93	125
Willow							
Willow	10	150	8	17	40	53	72
Willow	10	300	5	12	38	47	58
Willow	25	150	16	36	75	96	126
Willow	25	300	10	31	78	99	126
Willow	35	150	16	47	94	118	151
Willow	35	300	17	46	97	119	151
SEM (S*P*D)			0.6	1.2	2.5	3.5	4.9
Variable:					Probability		
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0480**	**0.0053**	0.1432	0.2318	0.6574
S*P			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*D			**0.0001**	**0.0390**	0.8534	0.2274	0.0653
P*D			**0.0001**	0.0588	**0.0024**	**0.0005**	**0.0001**
S*P*D			**0.0002**	0.8635	0.0776	**0.0139**	**0.0218**

4.3.4.3 Shoot diameter

There was a significant interaction between species, stem diameter and planting depth on shoot diameter at 164 DAP (Table 4.4). The interaction was because poplar of 10, 25 and 35 mm diameter stems, planted at 300 mm produced thicker shoots than at 150 mm planting depth, whereas willow produced similar shoot diameters at 150 and 300 mm planting depths. Significant interactions were also found between species and stem diameter, and species and planting depth at 93 DAP and 198 DAP, respectively. Stem diameter and planting depth had a significant interaction only at 164 and 198 DAP. No significant interactions were found for other observation dates. The interaction of species and stem diameter at 93 DAP, was because the stem diameter of willow was in the order 35 mm > 25 mm > 10 mm, whereas for poplar it was 35 mm > 25 mm = 10 mm. Stem diameter and planting depth

interacted for shoot diameter at 164 and 198 DAP because stem diameters of 35 and 25 mm produced thicker shoots at the planting depth of 300 mm, but 10 mm stems produced thicker shoots at 150 mm planting depth.

Species and stem diameter had significant effects ($P < 0.05$) on shoot diameter (Table 4.4). At 198 DAP, poplar produced thicker shoots than willow (10 mm vs 8 mm). Thick stem cuttings produced thicker shoots than thin stem cuttings ($P < 0.05$). For example at 198 DAP, 35 mm stem cuttings (11 mm) produced thicker shoot than 25 mm (9 mm) and 10 mm (7 mm) stems. However, no significant effect was found for planting depth on shoot diameter except at 93 DAP, when planting depth of 150 mm produced thicker shoots than 300 mm planting depth (3.8 mm vs 3.5 mm).

Table 4.4 Effects of stem diameter and planting depth of willow and poplar on shoot diameter.

Species	Cutting length (mm)	Planting depth (cm)	Shoot diameter (mm) Days after planting 93	133	164	198
Poplar	10	15	3.2	6.9	6.3	8.7
Poplar	10	30	3.0	4.1	7.7	7.1
Poplar	25	15	3.2	6.3	8.1	10.0
Poplar	25	30	2.9	6.4	8.7	10.9
Poplar	35	15	4.4	7.1	8.7	11.2
Poplar	35	30	4.0	8.0	10.1	12.9
Willow	10	15	2.6	3.6	4.3	6.2
Willow	10	30	2.1	3.3	3.9	4.5
Willow	25	15	4.4	6.1	7.0	8.5
Willow	25	30	3.8	6.1	7.0	8.5
Willow	35	15	5.2	7.2	8.4	10.2
Willow	35	30	5.2	7.3	8.5	9.8
SEM (S*P*D)			0.2	0.6	0.3	0.5
Variable:			Probability			
Species (S)			**0.0001**	**0.0280**	**0.0001**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0152**	0.5362	0.6855	0.9862
S*P			0.0001	0.0766	0.5431	0.8969
S*D			0.4944	0.6811	0.2187	**0.0144**
P*D			0.5485	0.0610	**0.0014**	**0.0082**
S*P*D			0.2632	0.1447	**0.0300**	0.3219

4.3.4.4 Tree height

There were significant (P<0.05) interactions between (i) species and planting depth, and (ii) stem diameter and planting depth on tree height. Significant interaction was also found between species and stem diameter on tree height at 133 DAP (Table 4.5). No other significant interaction effects were observed at any other time. For example, at 198 DAP, willow planted at 150 mm depth was taller than when planted at 300 mm depth (177 cm vs 165 cm), whereas poplar was significantly taller at a planting depth of 300 mm than 150 mm (156 cm vs 140 cm) (Table 4.5).

Species and stem diameter had significant effects on tree height (P<0.001). At 198 DAP, the mean height of willow (171 cm) was higher than for poplar (148 cm), and a similar trend was observed on the other observation dates. Thick stems produced taller trees than thin stems.

Table 4.5 Effects of stem diameter and planting depth of willow and poplar on tree height.

Species	Stem diameter (mm)	Planting depth (mm)	Tree height (cm) Days after planting 133	164	198
Poplar	10	150	62	76	104
Poplar	10	300	52	69	91
Poplar	25	150	86	108	143
Poplar	25	300	92	130	171
Poplar	35	150	98	129	173
Poplar	35	300	100	141	190
Willow	10	150	91	109	132
Willow	10	300	75	88	105
Willow	25	150	130	159	191
Willow	25	300	117	151	181
Willow	35	150	145	175	208
Willow	35	300	138	167	203
SEM (S*P*D)			3.9	4.4	5.6
Variable:				Probability	
Species (S)			**0.0001**	**0.0001**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			0.1491	0.6223	0.9792
S*P			**0.0172**	0.2170	0.6137
S*D			**0.0007**	**0.0001**	**0.0001**
P*D			**0.0047**	**0.0019**	**0.0002**
S*P*D			0.0711	0.5166	0.4198

4.3.4.5 Canopy diameter

Interaction of species and stem diameter had significant effects (P=0.0001) on canopy diameter throughout the study period (Table 4.6). For instance at 198 DAP, willow with 35 mm (76 cm vs 50 cm) and 25 mm (59 cm vs 43 cm) diameter stems produced a greater canopy diameter than poplar, but no difference was found for 10 mm diameter stems (34 cm vs 34 c m). There was an interaction ($P < 0.05$) between stem diameter and planting depth at all times, except at 93 DAP when the interaction was not significant. No significant effect was found for the interaction between species, stem diameter and planting depth during the study. The interaction ($P < 0.05$) between species and planting depth at 93 and 198 DAP was due to greater canopy diameter for willow planted at 150 mm depth than at 300 mm depth, whereas poplar produced greater canopy diameter at the 300 mm planting depth.

Willow produced greater canopy diameter ($P < 0.001$) than poplar at all times. At 198 DAP, mean canopy diameter of willow was 57 cm compared with 43 cm for poplar. Thick stem cuttings produced greater canopy diameter than thin stems ($P < 0.001$). For example at 198 DAP, 35 mm diameter stems produced greater canopy diameter compared to the 25 mm and 10 mm stems with means of 63 cm, 50 cm and 34 cm, respectively. A similar trend was found for the other dates of measurement. No significant effect was found for planting depth on canopy diameter, except at 133 and 164 DAP (Table, 4.6), when large canopy diameter was found for trees established from 300 mm planting depth than 150 mm depth (39 cm vs 36 cm and 43 cm vs 41 cm for 93 DAP and 133 DAP, respectively) .

Table 4.6 Effects of stem diameter and planting depth of willow and poplar on canopy diameter.

Species	Stem diameter (mm)	Planting depth (mm)	Canopy diameter (cm) Days after planting			
			93	133	164	198
Poplar	10	150	12.8	24.8	27.1	33.5
Poplar	10	300	14.8	25.1	29	35.3
Poplar	25	150	17.8	28.9	35.5	39.8
Poplar	25	300	22.7	34.2	41	46.3
Poplar	35	150	25.8	36.9	41.3	47.5
Poplar	35	300	23.4	39.5	47.2	52.3
Willow	10	150	16.5	23.5	30	41.5
Willow	10	300	12.2	22.3	24.1	26.5
Willow	25	150	28	43	46.5	55.7
Willow	25	300	24.8	47	51.8	62.9
Willow	35	150	41	55.8	62.5	77
Willow	35	300	39.5	60.2	66	74.2
SEM (S*P*D)			1.8	1.8	1.8	2.7
Variable:			Probability			
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			0.705	**0.0025**	**0.0096**	0.8642
S*P			**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*D			**0.0254**	0.6058	0.0826	**0.0051**
P*D			0.3866	**0.0257**	**0.0079**	**0.0024**
S*P*D			0.1392	0.0816	0.3724	0.1161

4.3.5 Effect of stem diameter and planting depth on biomass production

4.3.5.1 Above-ground biomass production

Edible DM was affected by the interaction of stem diameter and species at 150 DAP (Table 4.7). Willow stem cuttings of 35 mm diameter produced more edible DM than the 25 mm and 10 mm diameter stems (65 g/tree, 41 g/tree and 14 g/tree, respectively). A similar pattern was observed for poplar. No other significant interaction effects were observed at 150 DAP and 225 DAP.

Thick stems produced higher edible dry matter than thin stems for both species ($P < 0.001$). However, there was no significant effect of planting depth on edible DM (Table 4.7).

There were no significant interactions between any of the treatments for total shoot DM (Table 4.8). Stem diameter significantly affected (P<0.0001) total shoot DM at 150 DAP and 225 DAP. For example at 225 DAP, 35 mm diameter stems (654 g/tree) produced higher total shoot biomass than 25 mm (309 g/tree) and 10 mm (96 g/tree) diameter stems.

Table 4.7 Effects of stem diameter and planting depth on edible DM of willow and poplar.

Species	Stem diameter (mm)	Planting depth (cm)	Edible DM (g/tree) Days after planting 150	225
Poplar	10	150	27	44
Poplar	10	300	12	38
Poplar	25	150	30	65
Poplar	25	300	33	69
Poplar	35	150	35	154
Poplar	35	300	32	158
Willow	10	150	18	28
Willow	10	300	9	21
Willow	25	150	44	89
Willow	25	300	38	68
Willow	35	150	64	134
Willow	35	300	65	91
SEM (S*P*D)			9.9	21.6
Variable:			Probability	
Species (S)			0.0540	0.2156
Stem diameter (P)			**0.0005**	**0.0001**
Planting depth (D)			0.3878	0.3759
S*P			**0.0488**	0.2184
S*D			0.9839	0.3528
P*D			0.6898	0.7686
S*P*D			0.8577	0.7686

Table 4.8 Effects of stem diameter and planting depth on total DM for willow and poplar.

Species	Stem diameter	Planting depth	Total DM (g/tree) Days after planting	
	(mm)	(cm)	150	225
Poplar	10	150	55	116
Poplar	10	300	44	112
Poplar	25	150	156	281
Poplar	25	300	187	333
Poplar	35	150	365	713
Poplar	35	300	214	743
Willow	10	150	60	93
Willow	10	300	39	64
Willow	25	150	214	327
Willow	25	300	165	296
Willow	35	150	347	654
Willow	35	300	403	508
SEM (S*P*D)			38.8	84.8
Variable:			Probability	
Species (S)			0.1406	0.2375
Stem diameter (P)			**0.0001**	**0.0001**
Planting depth (D)			0.2912	0.6696
S*P			0.2808	0.4398
S*D			0.3958	0.3443
P*D			0.7624	0.8482
S*P*D			0.1327	0.8199

4.3.5.2 Below-ground biomass production

4.3.5.2.1 Root number

There was an interaction ($P < 0.05$) between species and stem diameter on the number of roots/tree (Table 4.9)(Photos 4.2 & 4.3). For example, at 225 DAP, 35 mm diameter willow stems had higher root number than 25 mm and 10 mm diameter stem cuttings (130, 102 and 52, respectively), whereas poplar stem diameter had no effect. No significant effects were observed for the other treatment interactions (Table 4.9).

There were significant effects of species and stem diameter on root number ($P<0.05$). For example at 225 DAP, mean root number was about three times

higher for willow than poplar (95 vs 30). Higher root number was observed at 35 mm (82) and 25 mm (67) stem diameters than 10 mm diameter (37). Planting depth had no effect on root number (Table 4.9).

Table 4.9 Effects of stem diameter and planting depth of 600 mm stakes of willow and poplar on root number per tree.

Species	Stem diameter (mm)	Planting depth (cm)	Root number/tree Days after planting 150	225
Poplar	10	15	17	29
Poplar	10	30	17	17
Poplar	25	15	27	22
Poplar	25	30	32	41
Poplar	35	15	17	23
Poplar	35	30	18	45
Willow	10	15	34	54
Willow	10	30	38	49
Willow	25	15	65	91
Willow	25	30	67	114
Willow	35	15	91	138
Willow	35	30	123	121
SEM (S*P*D)			6.4	14.9
Variable:			Probability	
Species (S)			**0.0001**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0012**
Planting depth (D)			0.0649	0.5625
S*P			**0.0001**	**0.0141**
S*D			0.1843	0.5796
P*D			0.2315	0.3916
S*P*D			0.1570	0.4855

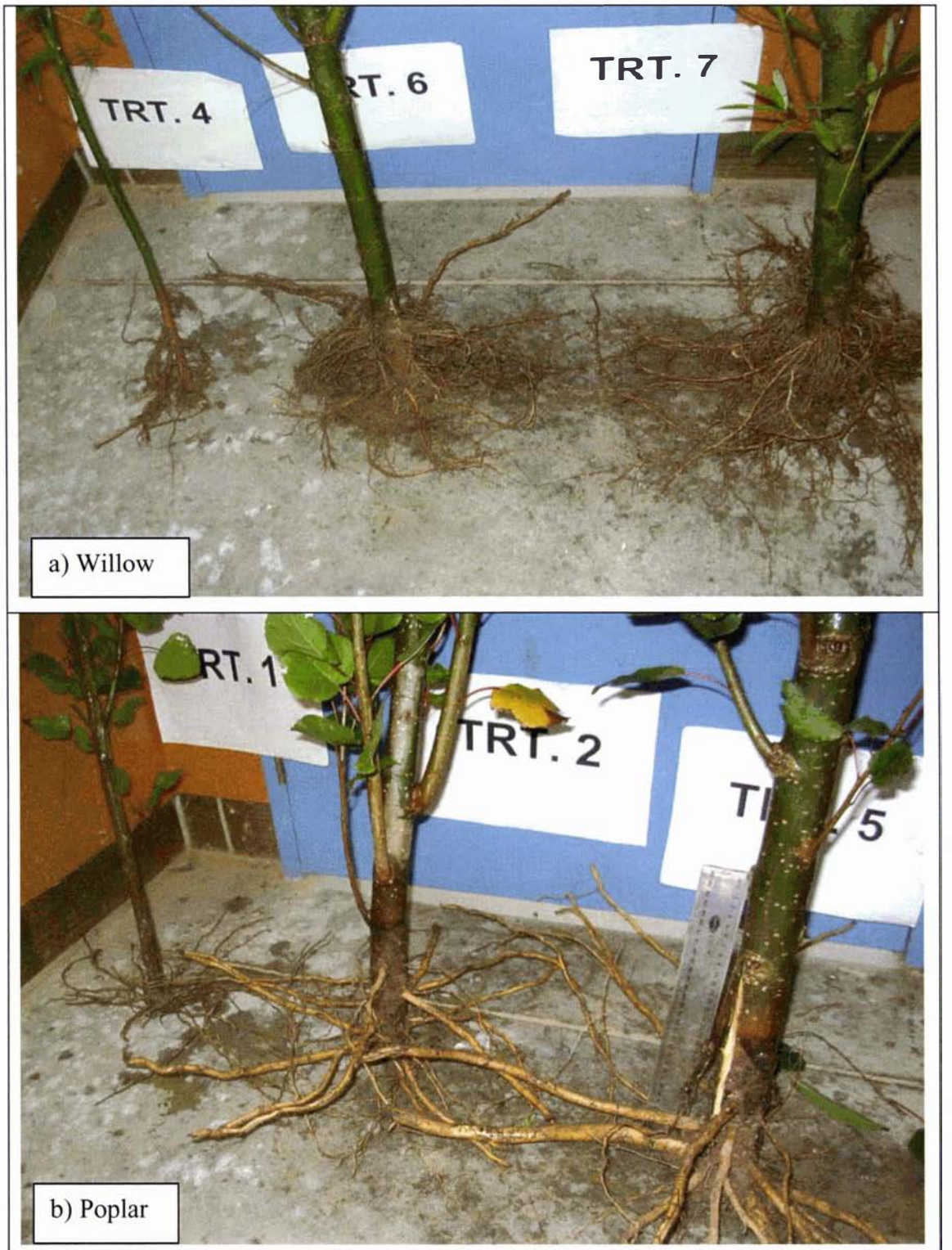

Photo 4.2 Root growth at 150 mm depth of a) willow and b) poplar established from stem cuttings of 10 mm (TRT. 4 & 1), 25 mm (TRT. 6 & 2) and 35 mm (TRT. 7 & 5) stem diameter (225 days after planting).

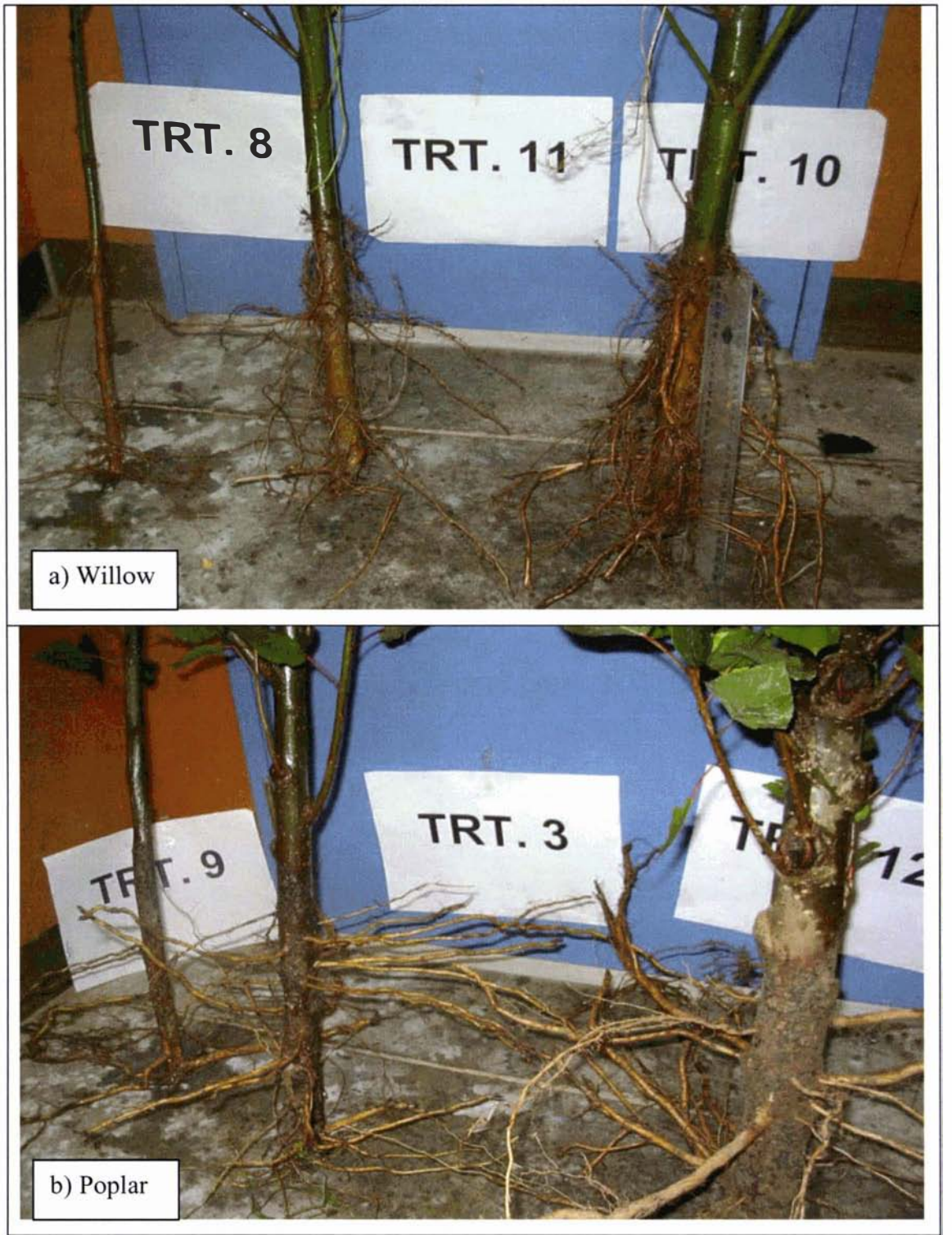

Photo 4.3 Root growth at 300 mm depth of a) willow and b) poplar established from stakes of 10 mm (TRT. 8 & 9), 25 mm (TRT. 11 & 3) and 35 mm (TRT 10 & 12) stem diameter (225 days after planting).

4.3.5.2.2 Root length and root length/volume ratio

There was an interaction (P=0.0005) between species and stem diameter on total root length at 150 DAP (Table 4.10). Trees established from 35 mm diameter willow stem cuttings had greater total root length than 25 mm and 10 mm diameter stem cuttings (1068 cm, 690 cm and 261 cm respectively), whereas poplar stem diameter had no effect on total root length.

Species and stem diameter significantly ($P < 0.05$) affected total root length. For example at 225 DAP, willow produced greater total root length than poplar (1194 cm vs 541 cm). Stem cuttings of 35 mm and 25 mm diameter produced greater total root length than 10 mm stems (1346 cm, 911 cm and 345 cm respectively). However, planting depth had no effect on total root length.

Root length/volume ratio (R_{LV} ratio) was affected by interaction of species and planting depth at 225 DAP (Table 4.10). Willow planted at 300 mm depth had higher ($P < 0.0394$) R_{LV} ratio than 150 mm depth (59:1 vs 34:1, respectively). There was no significant difference between poplar established at 150 mm and 300 mm depths on R_{LV} ratio.

There were significant effects of species ($P < 0.0001$), stem diameter ($P < 0.015$) and planting depth ($P < 0.0394$) on R_{LV} ratio at 225 DAP. Willow had higher R_{LV} ratio than poplar (47:1 vs 15:1, respectively). Higher R_{LV} ratio indicated that willow produced longer and thinner roots than poplar. Stems of 35 mm and 25 mm diameters had lower R_{LV} ratio than 10 mm stem diameters (20:1 = 29: 1 < 43:1, respectively). Stem cuttings established at 300 mm planting depth had higher R_{LV} ratio than 150 mm depth (38:1 > 23:1, respectively).

Table 4.10 Effects of stem diameter and planting depth for 600 mm stem cuttings of willow and poplar on total root length and total root length/volume ratio.

Species	Stem diameter (mm)	Planting depth (mm)	Total root length (cm) Days after planting 150	Total root length (cm) Days after planting 225	R_{LV} ratio Days after planting 225
Poplar	10	150	204	423	19
Poplar	10	300	157	199	27
Poplar	25	150	416	475	14
Poplar	25	300	353	598	18
Poplar	35	150	279	594	3
Poplar	35	300	216	959	8
Willow	10	150	302	462	42
Willow	10	300	219	295	86
Willow	25	150	790	1334	31
Willow	25	300	590	1237	52
Willow	35	150	1162	2473	30
Willow	35	300	975	1359	40
SEM (S*P*D)			115.2	304.5	7.8
Variable:				Probability	
Species (S)			**0.0001**	**0.0012**	**0.0001**
Stem diameter (P)			**0.0001**	**0.0005**	**0.0015**
Planting depth (D)			0.1224	0.303	**0.0025**
S*P			**0.0005**	0.0613	0.3732
S*D			0.4633	0.1337	**0.0394**
P*D			0.9028	0.6719	0.2506
S*P*D			0.9446	0.1873	0.388

4.3.5.2.3 Root volume

No significant interaction effects on root DM were found (Table 4.11). Species and stem diameter significantly affected root volume/tree ($P < 0.05$). For example at 225 DAP, poplar produced higher root volume/tree than willow (78 cm^3/tree vs 36 cm^3/tree), and root volume was significantly higher ($P= 0.0007$) for trees established from 35 mm than those from 25 mm and 10 mm diameter stems with means of 114 cm^3/tree, 44 cm^3/tree, and 15 cm^3/tree, respectively. There was no significant effect of planting depth on root volume (Table 4.11).

Table 4.11 Effects of stem diameter and planting depth for 600 mm stakes of willow and poplar on root volume.

Species	Stem diameter (mm)	Planting depth (mm)	Root volume (cm^3) Days after planting	
			150	225
Poplar	10	150	3	25
Poplar	10	300	2	16
Poplar	25	150	9	53
Poplar	25	300	6	47
Poplar	35	150	10	196
Poplar	35	300	4	133
Willow	10	150	4	13
Willow	10	300	1	4
Willow	25	150	13	51
Willow	25	300	9	24
Willow	35	150	22	92
Willow	35	300	13	35
SEM (S*P*D)			4	32
Variable			Probability	
Species (S)			**0.0368**	**0.0311**
Stem diameter (P)			**0.0051**	**0.0007**
Planting depth (D)			0.0621	0.1289
S*P			0.1441	0.0940
S*D			0.5468	0.8814
P*D			0.5952	0.4812
S*P*D			0.8854	0.8027

4.3.5.2.4 Root dry matter.

No significant interaction effects on root DM were found (Table 4.12). Species and stem diameter significantly ($P < 0.05$) affected root DM. For example at 225 DAP, poplar produced higher root DM than willow (27.7 g/tree vs 12.0 g/tree). Root DM was significantly higher for the 35 mm stem diameter than 25 mm and 10 mm diameters with means of 40.7 g/tree, 14.3 g/tree and 4.4 g/tree respectively. There was also a significant planting depth effect on root DM at 150 DAP, which 150 mm planting depth produced higher root DM than 300 mm (3.5 g/tree vs 1.7 g/tree), but no significant effect was found at 225 DAP (Table 4.12).

There were no significant interactions between any of the treatments for percentage (%) of root DM (Table 4.12). Poplar produced higher % of root DM than willow (6% vs 3%, respectively). Stem cuttings of 35 mm diameter produced higher % of root DM than 25 mm and 10 mm diameter stems (5% >

4% = 4 %). Tree established from 150 mm planting depth produced higher % of root than 300 mm depth with means of 5% and 3%, respectively.

Table 4.12 Effects of stem diameter and planting depth of willow and poplar on root dry matter.

Species	Stem diameter (mm)	Planting depth (mm)	Root DM(g/tree) Days after planting 150	Root DM(g/tree) Days after planting 225	% of root DM Days after planting 225
Poplar	10	150	0.9	8.2	6.0
Poplar	10	300	0.3	4.8	4.0
Poplar	25	150	3.0	18.1	6.0
Poplar	25	300	1.7	16.0	4.0
Poplar	35	150	3.2	66.9	8.0
Poplar	35	300	1.6	52.2	6.0
Willow	10	150	1.2	4.0	3.0
Willow	10	300	0.3	1.0	1.0
Willow	25	150	5.0	15.1	4.0
Willow	25	300	2.6	8.1	3.0
Willow	35	150	7.9	29.2	4.0
Willow	35	300	3.8	14.3	3.0
SEM (S*P*D)			1.7	10.4	0.8
Variable;				Probability	
Species (S)			**0.0223**	**0.0152**	**0.0001**
Stem diameter (P)			**0.0014**	**0.0002**	**0.0182**
Planting depth (D)			**0.0147**	0.2226	**0.0009**
S*P			0.1620	0.0516	0.1276
S*D			0.3494	0.897	0.7141
P*D			0.4529	0.6907	0.7850
S*P*D			0.8144	0.9807	1.0000

Based on the results of total shoot DM and root DM measured at 225 DAP, there were strong correlations between edible DM and root DM (Figure 4.3) and total shoot DM and root DM (Figure 4.4). Higher root DM, particularly from thick stems, produced higher edible and total shoot DM.

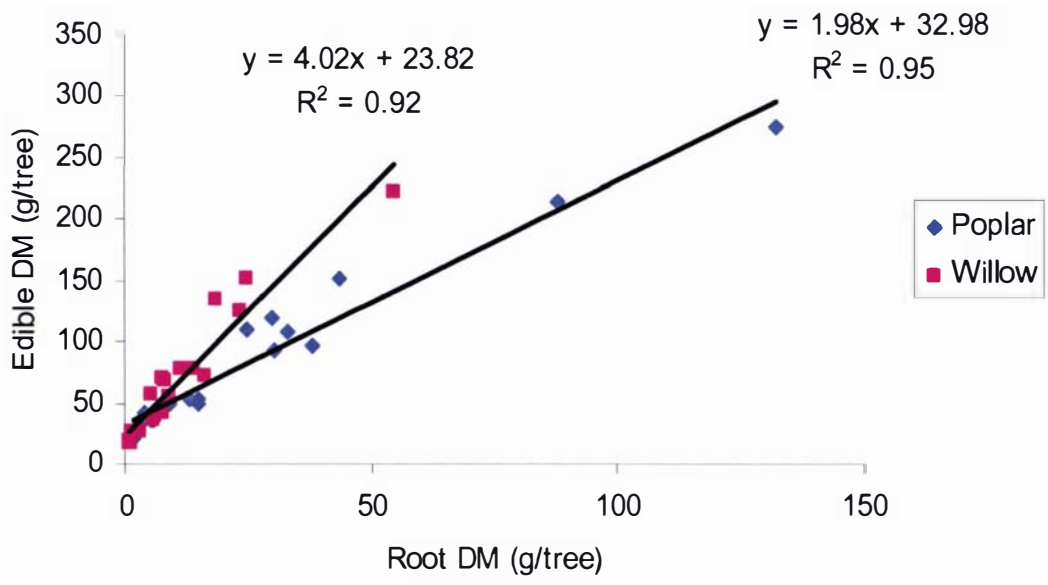

Figure 4.3 Relationship between edible DM and root DM of willow (n=18, P = 0.0001) and poplar (n= 18, P = 0.0001).

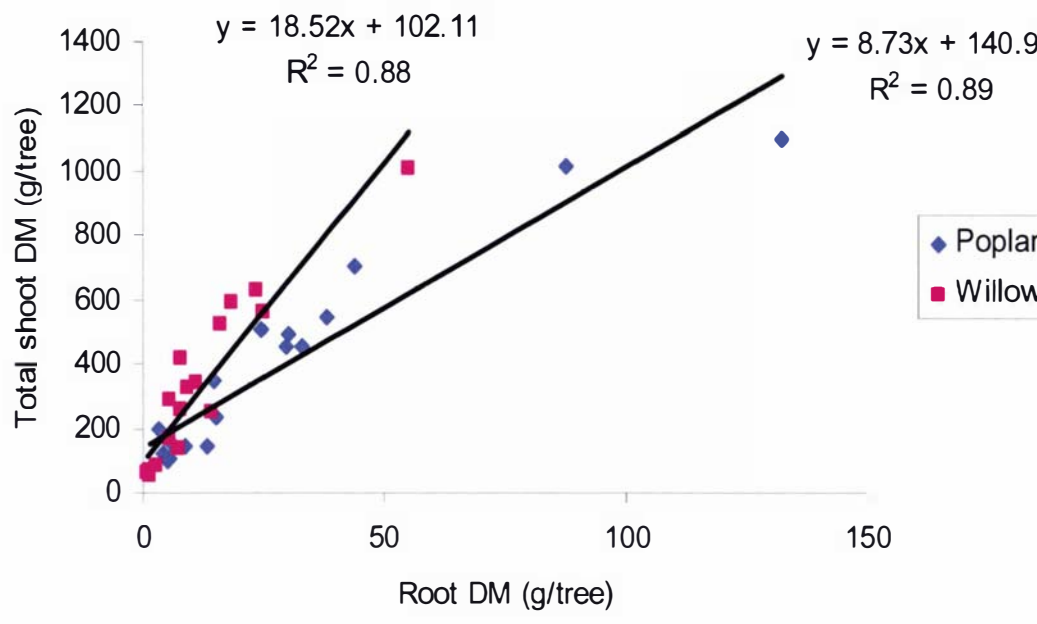

Figure 4.4 Relationship between total shoot DM and root DM of willow (n=18, P = 0.0001) and poplar (n=18, P = 0.0001).

4.4 Discussion

4.4.1 Tree survival and soil water content (SWC).

The high survival rate for the willow clone 'Tangoio' and poplar clone 'Veronese' was aided by the high rainfall (887 mm) and soil moisture during the establishment growing season (August 2003 to March 2004). The major limitations for establishment of willow are inadequate soil moisture and excessive weed competition (Hathaway 1986; Hudson 1997). Nevertheless, survival was greater for trees established from 35 mm and 25 mm diameter stem cuttings (600 mm long) than 10 mm diameter stem cuttings. Observations in the literature support the finding that size of stem cutting affects tree survival during establishment (Zierke 1994; Hoag 2004), and this may be because of higher nutrient and carbohydrate reserve (Zierke 1994; Macpherson 1995; Hoag 2004). Thick stems also resulted in greater root production, which could have increased water and nutrient uptake to the establishing trees. The result was in line with Ahmed *el al*. (2003), who found that better rooting was associated with better survival rate.

Control of competition from pasture and weed species improves tree establishment (Abrahamson *et al*. 2002). Understorey pasture and weeds in this experiment were controlled by a combination of herbicides and manual weeding which minimised weed competition and ensured better growth and higher survival.

4.5.2 Tree growth and biomass

Higher root growth and above-ground biomass of willow and poplar was because of favourable weather conditions. However low soil moisture conditions can significantly reduce root development and delay sprouting of several clones of poplar (Hansen & Phipps 1983) which reduces growth and biomass production.

Willow and poplar growth were more strongly influenced by stem diameter than planting depth. The thickest stems (35 mm diameter) of both willow and poplar

produced higher shoot number and length, tree height, root number and length, root DM, and edible and total shoot DM than trees established from 10 mm diameter stem cuttings. This result was supported by the strong correlation between physical size of cutting and poplar growth (Bowersox 2001).

Root DM was strongly related to edible DM and total DM of willow and poplar (Figures 4.4 & 4.5). This was supported by Heilman *et al.* (1994) who found significant relationships between above-ground weights and weights of first-order roots of hybrid poplar (*Populus trichocarpa x P. deltoides*). Thick stems produced higher root DM and higher shoot growth, leading to higher edible and total biomass compared to thin stems. This was possibly because thick stem cuttings having a large nutrient and carbohydrate reserve (Zierke 1994; Macpherson 1995) to support early root and vegetative growth. Higher survival for trees established from 35 mm and 25 mm diameter stem cuttings during the short drought period from 31 December 2003 to 5 January 2004 may have been because of the higher root DM production from thick stem cuttings. Both willow and poplar at 150 days after planting produced low root DM. If dry periods occur immediately after such a period, when there are not enough roots to uptake water, stem cuttings planted tend to die. Now there can be two indications to follow i) planting should be in early August so that there are enough roots produced before dry summers start or ii) find low cost irrigation facilities if possible.

An interesting result was that 10 mm diameter poplar stem cuttings produced higher shoot numbers than thicker stem cuttings up to 62 DAP (Table 4.2). This might be because thin stems of poplar produced earlier roots, leading to increased absorption of nutrients for buds to sprout. This was supported by Ahmad *et al.* (2003) who found that more roots resulted in fewer days required for the buds to sprout from plum (GF-655), peach almond (GF-677) and hybrid seedlings of almond-peach. Furthermore, Howard *et al.* (1969) found cuttings made from thin shoots of plum generally rooted more readily than those from thick stems. Usually there were no differences in shoot number between thin and thick stem cuttings of poplar after 62 DAP. In contrast to this trend, willow

with thick stem cuttings consistently produced a greater shoot number than thin stem cuttings, resulting in higher biomass for thick stem cuttings.

Poplar produced greater root biomass than willow, although higher root number and length were found for willow. This was due to poplar producing low R_{LV} ratio (root length/root volume) with short and thicker roots (Figure 4.6), resulting in higher root biomass. There was no advantage to growth and biomass production in planting willow and poplar at 150 mm or 300 mm depth. Planting depth was clearly not an important factor influencing early tree growth and biomass production during the prevailing favourable weather conditions (2003/2004). Similarly Hansen *et al.* (1991) found no effect of planting depth on either height or growth of hybrid poplar clones DN 170, DN-154, NE-387 and NE-20. Under favourable weather conditions and high soil water content (SWC), the majority of observed roots of willow and poplar in this trial were concentrated in the 0-150 mm soil layer. Ericsson (1984)(cited by Volk *et al.* 2001) found the majority of root biomass of *Salix dasyclados* in the top 120 mm of the soil. However, Rytter *et al.* (1996) showed under water stress that the roots of *Salix viminalis* grew deeper into the soil profile. The general lack of interactions between species, stem diameter and planting depth on root and above-ground biomass in this study may have been because of the similar results on the effects of planting depth. Beaton (1987) recommended deep planting of poles of poplar to improve tree stability.

A trial on the effect of sheep browsing on shoot utilisation, tree damage and identifying a suitable height of tree browsing needs to be carried out, to ensure willow and poplar are eaten by sheep and can withstand sheep grazing without any serious impact.

The purpose of using thin stems was to reduce the cost of field establishment. The result found growth and biomass production of willow and poplar from thin stem cuttings was not promising. Nevertheless, the cost of stem cuttings may be at least double or triple between 35 mm, 25 mm and 10 mm diameter stem cuttings, but the higher edible DM (654 g/tree (6540 kg/ha) > 309 g/tree (3090 kg/ha) > 96 g/tree (960 kg/ha), respectively) and better survival from thick stem cuttings may compensate for the extra start-up cost during field establishment.

It is recommended that farmers establishing willow and poplar for fodder plant thick stems (35 mm) for higher tree growth and biomass production. However, to make establishment cost effective, 25 mm diameter stems can also be used because they have a similar rate of survival as 35 mm diameter stems.

4.5 Conclusions

It is concluded that: (i) Higher survival rates were found for thick and intermediate stem cuttings of 35 mm and 25 mm, ii) thick stem cuttings (35 mm) of willow and poplar had greater shoot and root production than intermediate (25 mm) and thin stems (10 mm), and iii) 35 mm stem cuttings are recommended for establishing fodder blocks for higher biomass production. However, for cost-effective utilisation, available resources from intermediate (25 mm) stem diameters may need to be considered. The results clearly indicated that planting depth did not influence above-ground biomass production.

Further studies are needed to determine the rooting ability of different stems involving apical soft wood, semi-hard wood and hard wood to improve the understanding of rooting behaviour of willow and poplar. It will also help to understand the role of carbohydrate reserves on growth. As the time of cutting of willow and poplar canopy may also have considerable influence on the efficiency of rooting and canopy regrowth patterns, studies are required to determine the optimum period of cutting harvest.

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5 Effect of horizontal planting of willow and poplar of various stem lengths and planting depths on survival, growth and biomass production

5.1 Introduction

One of the most important characteristics of many tree species including willow and poplar is their readiness to propagate vegetatively from stem cuttings (Zsuffa 1992). Establishment in the field requires a large number of cuttings and it can be costly, inconvenient, and impractical if parent trees from which cuttings could be obtained are not available locally. One way to reduce planting material cost would be to use small cuttings. According to van Kraayenoord *et al.* (1986) willow and poplar can be established through vertical or horizontal planting. The horizontal planting method is also practised with other plant species such as *Gliricidia sepum* (Ybalmea *et al.* 2000) and *Dalbergia sissoo* (Chaturvedi 2001). The orientation of planting influences growth characteristics with cuttings of *Dalbergia sissoo* planted vertically sprouting and developing foliage quicker than cuttings planted at an angle or horizontally. *Dalbergia sissoo* tree height, diameter increment and number of roots per plant were greater from horizontal planting (Chaturvedi 2001). Similarly, Ybalmea *et al.* (2000) found stem diameters of *Gliricidia sepum* planted horizontally influence shoot growth, but there was no significant effect of stem length. However there is negligible information to suggest horizontal planting of willow and poplar has any beneficial effect on biomass.

The quality of stem cutting is important for good establishment and biomass production. According to Anon (2004) the quality of stem cuttings depends on their age, thickness, number of nodes and health. Stem cuttings of willow and poplar are normally selected from branches or stems aged one year (FAO 1979). Horizons Regional Council (2006) uses 1 m to 3.5 m long poles of willow and poplar for soil erosion control and fodder blocks in Manawatu, North Island, New Zealand. Likewise, Snow *et al.* (2003) also used 1 m stakes of willow and poplar for a dairy effluent study. Smaller stem cuttings such as 250 mm long, 10 mm diameter were planted in cultivated soil in New Zealand (Hathaway 1980). The experiment described in Chapter 4 found stem cuttings of 25 to 35 mm diameter planted vertically had higher survival and biomass production. However information was not enough to suggest and compare performance of willow and poplar planting horizontally. Field experience shows

that horizontal planting can be a potential method for low cost planting of willow and poplar. Therefore, in this Chapter horizontal planting was investigated. This research aimed to (i) determine the effect of horizontal planting of three stem cutting lengths and two planting depths on survival, growth and shoot biomass of willow and poplar, and to (ii) determine the effect of stem length and planting depth on root biomass.

5.2 Material and methods.

5.2.1 Experimental site

The research was conducted at the Pasture and Crop Unit, Moginie Massey University Palmerston North, New Zealand (longitude 175 ° 37' E, latitude 40 ° 21' S, altitude 30 m above sea level) on a Tokomaru silt loam with aeric fragiaqualf (gleyed yellow-grey earth) from 6 August 2003 to 31 March 2004. Rainfall and temperature data during the growing season were obtained from AgResearch Grasslands, Palmerston North, 2.5 km from the experimental site, and are presented in Section 4.4.1.

Existing weeds were eradicated using Roundup Renew XTRA at 2.25 l/ha (a.i.= 490 g glyphosate/l) on 24 July 2003 before planting. When plants were covered by weeds, manual weeding using secateur was conducted on 25 October 2003 to reduce competition against willow and poplar in the early stages of growth, followed by spraying of Versatill with care at 1 l/ha (a.i. = 300g clopyralid/l) on 12 December 2003. However, Versatill did not effectively control the major weeds especially clustered dock (*Rumex conglomeratus* Murr) and therefore further manual weeding was conducted on 29 and 30 January 2004. On 28 February 2004 the insecticide Orthene (a.i. = 195 g/l accephate plus 346 g/l ethylene glycol) was sprayed to control sawfly (*Nematus oligospilus*).

5.2.2 Experimental treatments and design

Stem cuttings from one year old shoots were planted on 6 August 2003 at a 1.0 m x 1.0 m planting distance (10,000 trees/ha). The planting material was collected from Greater Wellington Regional Council's Akura nursery, Masterton, on 4 July, 2003, and stored in a cool room (8 °C) for 30 days. All the planting material was soaked in water for 48 hours before planting.

The treatments were:

i. Stem length: three stem lengths were: (i) 50 mm, (ii) 200 mm, and (iii) 600 mm, with mean stem cutting diameter 25 mm. The mean diameter of stems was measured at their midpoint.

ii. Planting depth: two planting depths were used: either (i) Stem cuttings pushed into the soil horizontally to a depth of 50 mm, or ii) Stem cuttings buried horizontally at a depth of 100 mm.

iii. Tree species; two tree species were: (i) Salix *matsudana x alba* (willow clone 'Tangoio'), (ii) *Populus deltoides x nigra* (poplar clone 'Veronese').

Each plot (experimental unit) was 5 m x 5 m, with 36 plants, and the factorial treatments (3 cutting lengths x 2 planting depths x 2 species) were arranged in three randomized complete blocks, giving a total of 36 plots.

5.2.3 Tree measurements

5.2.3.1 Shoot emergence and tree survival

Shoot emergence was assessed every fortnight from 24 September to 6 November 2003 in each plot followed by an assessment of tree survival on 11 March 2004.

5.2.3.2 Tree growth

Growth of willow and poplar planted horizontally was measured monthly in terms of shoot number, main shoot length, shoot diameter and maximum inter-row canopy diameter (measured perpendicular to the original planting row). In-row canopy diameter was only measured once, at the end of March 2004. Between five and eight trees per plot were assessed depending on tree survival.

5.2.3.3 Biomass of willow and poplar

5.2.3.3.1 Above-ground biomass

A total of 36 trees per harvest with 18 trees each of willow and poplar (1 tree per plot) were harvested twice; 6 January 2004 and 16 March 2004 to determine the effect of different cutting lengths and planting depths on above-ground biomass production. Harvested material was divided into edible (leaf and stem < 5mm diameter) and woody stem (stem > 5 mm diameter) (Kemp *et al*. 2003) and these were oven-dried at 80 ^{o}C for at least 48 hours to determine edible dry matter (DM) and total shoot DM production. Woody stem was oven-dried for 48 - 186 hours at 80 ^{o}C.

5.2.3.3.2 Below-ground biomass

Attributes measured were root number, root length, root volume and root DM and the same trees used for above-ground biomass were used. Roots were excavated from a pit size of 0.8 m x 0.5 m x 0.3 m. Root volume was measured

using measuring cylinders ranging in volume from 10 cm^3 to 200 cm^3. Root volume was estimated using the difference in water level before and after roots were immersed.

5.2.3.4 Soil water content

Volumetric soil water content (SWC) was measured monthly using Time Domain Reflectometry (TDR) (Parchomchuki *et al.* 1997). Twelve pairs of permanent TDR probes were inserted randomly around the experimental area approximately 150 mm away from the base of trees, at soil depths of 0-150 mm (6 pairs) and 0-300 mm (6 pairs).

5.2.4 Statistical analysis

All data were analysed by Analysis of Variance (ANOVA) using the PROC GLM procedure of SAS (SAS 2001) and mean separation was achieved using the Least Significant Difference test at the 5% significance level. The relationship between root DM and total shoot DM was determined using linear regression analysis.

5.3 Results

5.3.1 Rainfall and temperature

The total rainfall and mean temperature during the growing season of 2003/2004 were described in Section 4.4.1.

5.3.2 Soil water content

SWC from 13 October to 15 March 2004 is presented in Figure 5.1. SWC at 0-150 mm soil depth ranged from 29% to 46% and averaged 34%. SWC during summer was 29% (15 December 03), 30% (23 January 04) and 38% (25 February 04) (Figure 5.1).

At 0-300 mm depth, SWC ranged from 28% to 38% with a mean of 31%. On 15 December 03, 23 January 04 and 25 February 04, SWC was 28%, 27% and 35%, respectively (Figure 5.1).

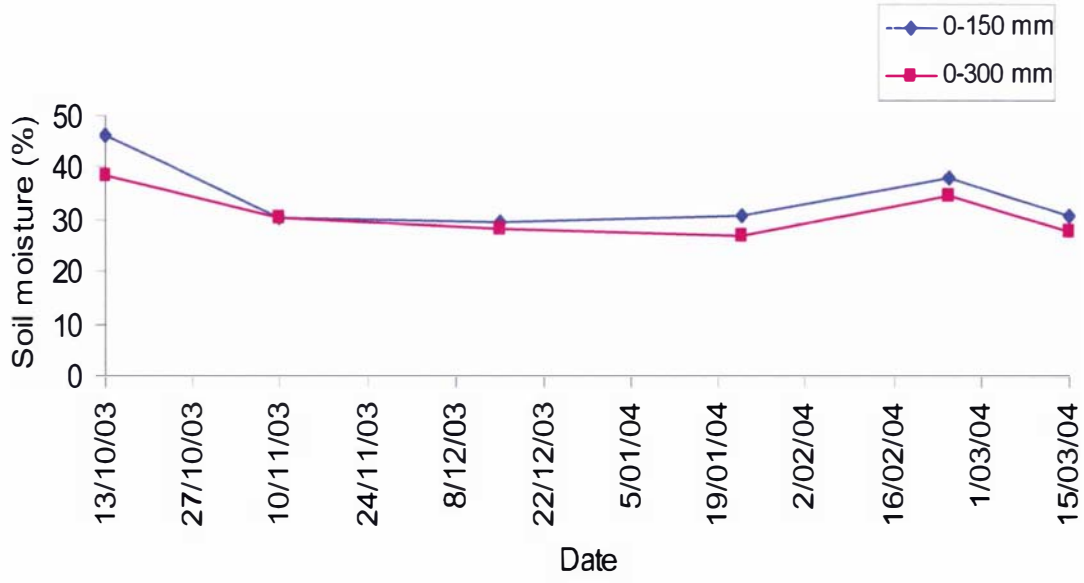

Figure 5.1 Volumetric soil water content (%) at 0-150 mm and 0-300 mm soil depth during the growing season at the experimental site at Massey University, Palmerston North.

5.3.3 Percentage of shoot emergence

There was significant ($P < 0.05$) interaction between species, stem length and planting depth on shoot emergence throughout the experimental period (Table 5.1). For example at 50 days after planting (DAP) willow of 600 mm stem length planted at 50 mm depth had higher shoot emergence than when planted at 100 mm depth with means of 95% and 31%, respectively. Similar results were found for 200 mm and 50 mm stem length planted at 50 mm and 100 mm depth. Poplar of 600 mm length had higher shoot emergence when planted at 50 mm than 100 mm depth (52% vs 0%). A similar result was found for 200 mm stem length (32% > 0%), but not for 50 mm stem length (2% = 0%). At 93 DAP poplar of 600 mm stem length produced higher shoot emergence at 50 mm planting depth than 100 mm depth (93% vs 24%). Similar results were found for 200 mm and 50 mm stem lengths with higher shoot emergence from 50 mm planting depth than 100 mm depth. Willow of 200 mm and 50 mm stem lengths had higher shoot emergence at 50 mm than 100 mm planting depth, but not for 600 stem length, where emergence from both planting depths was similar.

Species, stem length and planting depth significantly ($P < 0.0001$) affected shoot emergence (Table 5.1). For example at 50 DAP willow had higher shoot emergence than poplar (48% vs 14%, respectively). A similar pattern was observed on the other observation dates. Long stem cuttings had higher shoot emergence than short stems. For example at 50 DAP, 600 mm stem length had higher plant emergence than 200 mm and 50 mm stem lengths with means of 44% > 35% > 14%, respectively. A similar pattern was found for the other dates of survey. Planting depth of 50 mm produced higher shoot emergence than 100 mm (55% and 8% respectively) at 50 DAP. A similar result was found on the other observations dates.

Table 5.1 Effect on percentage of shoot emergence of horizontal planting at two depths and three stem lengths for willow and poplar.

Species	Treatments		Plants emergence (%)			
	Stem length (mm)	Planting depth (mm)	Days after planting			
			50	64	77	93
Poplar	50	50	2	3	6	42
Poplar	50	100	0	0	0	0
Poplar	200	50	32	45	57	72
Poplar	200	100	0	0	7	13
Poplar	600	50	52	71	81	93
Poplar	600	100	0	1	7	24
Willow	50	50	50	66	73	75
Willow	50	100	5	6	6	6
Willow	200	50	99	100	100	100
Willow	200	100	10	39	60	68
Willow	600	50	95	100	100	100
Willow	600	100	31	61	88	90
SEM (S*L*D)			2.4	3.8	3.1	8.4
Variable:			Probability:			
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem length(L)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*L			**0.0028**	0.0706	**0.0001**	0.2861
S*D			**0.0001**	**0.0048**	0.3171	**0.0267**
S*L*D			**0.0001**	**0.0001**	**0.0001**	**0.0237**

SEM : standard error of the least square means

5.3.4 Tree survival

There were no significant interactions between treatments on tree survival.

Species (P=0.0008), stem length (P=0.0001) and planting depth (P=0.0015) significantly affected tree survival (Table 5.2). Willow had significantly higher survival than poplar (71% vs 51%, respectively). Survival was higher for the 600 mm stem length (93%) compared with 200 mm (77%) and 50 mm (13%). Planting depth of 50 mm had higher survival than 100 mm depth (70% vs 52%, respectively).

Table 5.2 Effect on tree survival of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Tree Survival (%)
Species	Stem length (mm)	Planting depth (mm)	Days after planting 244
Poplar	50	50	1.0
Poplar	50	100	0.0
Poplar	200	50	80.3
Poplar	200	100	45.5
Poplar	600	50	95.2
Poplar	600	100	82.9
Willow	50	50	44.7
Willow	50	100	5.7
Willow	200	50	100.0
Willow	200	100	80.9
Willow	600	50	99.0
Willow	600	100	94.3
SEM (S*L*D)			8.7
Significance			
Species (S)			**0.0008**
Stem length (L)			**0.0001**
Planting depth (D)			**0.0015**
S*L			0.2487
S*D			0.6363
S*L*D			0.1492

SEM : standard error of the least square means

5.3.5 Effect of stem length and horizontal planting depth on tree growth

5.3.5.1 Shoot number

There were significant (P=0.0001) interactions between species, stem length and planting depth (Table 5.3). For example at 90 DAP, willow of 600 mm stem length produced more shoots when planted at 50 mm than 100 mm planting depth (14 vs 3). Similar trends were found for 200 mm and 50 mm stem lengths planted at 50 mm and 100 mm depths. Poplar of 600 mm (5 vs 0.1) and 200 mm stem lengths (2 vs 0) produced more shoots at 50 mm than 100 mm planting depth, but planting depth had no effect at 50 mm stem lengths. A similar trend was found at the other observations dates.

Table 5.3 Effect on shoot number of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Shoot number				
Species	Stem length (mm)	Planting depth (cm)	Days after planting				
			60	90	130	160	190
Poplar	50	50	0.04	0.00	0.00	0.00	0.00
Poplar	50	100	0.00	0.00	0.00	0.00	0.04
Poplar	200	50	1.79	1.92	1.88	1.57	1.57
Poplar	200	100	0.00	0.17	0.13	0.13	0.21
Poplar	600	50	4.83	5.21	5.17	5.13	4.96
Poplar	600	100	0.13	1.13	1.58	1.89	2.18
Willow	50	50	1.29	1.54	1.51	1.12	1.16
Willow	50	100	0.08	0.13	0.13	0.13	0.13
Willow	200	50	5.71	5.41	4.34	3.87	3.73
Willow	200	100	2.13	2.33	2.13	1.96	2.00
Willow	600	50	13.54	12.67	9.17	7.67	7.04
Willow	600	100	3.38	3.83	3.83	3.71	3.63
SEM (S*L*D)			0.25	0.28	0.23	0.23	0.22
Variable:			Probability				
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem length (L)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*L			**0.0001**	**0.0001**	**0.0001**	**0.0019**	**0.0091**
S*D			**0.0001**	**0.0001**	**0.0036**	0.0729	0.0677
S*L*D			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**

SEM : standard error of the least square means

5.3.5.2 Shoot length

There was significant (P=0.0001) interaction between species, stem length and planting depth on shoot length, throughout the dates of measurement (Table 5.4). For example at 60 DAP, willow of 600 mm stem length planted at 50 mm depth produced longer shoots than when planted at 100 mm planting depth (16.6 cm vs 12.8 cm). Similar trends were found for 200 mm and 50 mm stem lengths, planted at 50 mm and 100 mm depth. Poplar of 600 mm (12.2 cm vs 0.4 cm) and 200 mm stem lengths (5.7 cm vs 0.0 cm) produced longer shoots at the planting depth of 50 mm compared with 100 mm, but 50 mm stem lengths did not vary between planting depths. At 190 DAP, willow of 600 mm stem length produced longer shoots at 50 mm than 100 mm planting depth (169 vs 153 cm, respectively). A similar result was found for 50 mm stem length, but not for 200 mm stem length. Stem cuttings of 200 mm length produced comparable shoot lengths at 50 mm and 100 mm planting depths with means of 111 cm and 98 cm, respectively. Poplar of 600 mm stem lengths produced

longer shoots than medium (200 mm) and short stems (50 mm) at 50 mm than 100 mm planting depths.

Willow produced longer shoots (P=0.0001) than poplar (Table 5.4). At 190 DAP, the shoot length of willow was 101 cm, whereas poplar shoot length was 51 cm. Willow also produced longer shoots at early observations dates. Longer stems produced longer shoots than short stems (P=0.0001). For example at 190 DAP, 600 mm stem lengths produced longer shoots than 200 mm and 50 mm stems with means of 136 cm, 75 cm and 15 cm, respectively. A similar trend was found for other dates of measurement. Shoot length was greater (P = 0.0001) for planting depth of 50 mm than 100 mm (93 mm vs 60 cm, respectively) at 190 DAP. A similar trend was found on the other observation dates.

Table 5.4 Effect on shoot length of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Shoot length (cm)				
Species	Stem length (mm)	Planting depth (mm)	Days after planting				
			60	90	130	160	190
Poplar	50	50	0.1	0.2	0.0	0.0	0.0
Poplar	50	100	0.0	0.0	0.0	0.0	0.0
Poplar	200	50	5.7	12.9	47.3	62.2	79.9
Poplar	200	100	0.0	0.6	3.8	5.0	13.5
Poplar	600	50	12.2	25.9	75.1	96.6	125.0
Poplar	600	100	0.4	6.5	44.1	61.6	92.3
Willow	50	50	4.8	8.6	38.8	42.4	54.1
Willow	50	100	0.6	1.6	5.8	7.5	8.0
Willow	200	50	12.1	23.4	77.4	93.8	114.7
Willow	200	100	6.8	20.7	79.5	86.4	98.2
Willow	600	50	16.6	40.9	107.9	132.5	168.7
Willow	600	100	12.8	33.0	110.0	126.9	153.4
SEM (S*L*D)			0.5	0.9	2.5	3.2	3.9
Variable:			Probability				
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem length (L)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*L			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0017**
S*D			**0.0306**	**0.0005**	**0.0002**	**0.0068**	0.2336
S*L*D			**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0001**

SEM : standard error of the least square means

5.3.5.3 Shoot diameter

There was an interaction (P=0.0001) between species, stem length and planting depth on shoot diameter (Table 5.5). For example at 190 DAP, poplar of 600 mm (12.9 mm vs 9.9 mm) and 200 mm (8.8 mm vs 1.4 mm) stem lengths produced thicker shoots at 50 mm planting depth than 100 mm, but no significant difference in shoot diameter was detected between planting depth when 50 mm stem lengths were evaluated. A similar trend was observed on the other observation dates. Willow of 50 mm (4.0 mm vs 0.7 mm) stem length produced thicker shoots at 50 mm than 100 mm planting depth and similar results were found from 600 and 200 mm stem lengths. A similar trend was observed at 130 and 160 DAP.

Species, stem length and planting depth had significant effects on shoot diameter (P=0.0001). For example at 190 DAP, shoot diameter was greater for willow than poplar (7.0 mm vs 5.4 mm). Greater shoot diameter was observed from 600 mm (11.2 mm) than 200 mm (5.9 mm) and 50 mm (1.1 mm) stem lengths. Planting material at 50 mm soil depth produced greater shoot diameter than planting at 100 mm (7.5 mm vs 4.8 mm, respectively) (Table 5.5).

Table 5.5 Effect on shoot diameter of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Shoot diameter (mm)			
Species	Stem length (mm)	Planting depth (mm)	Days after planting			
			90	130	160	190
Poplar	50	50	0.1	0.0	0.0	0.0
Poplar	50	100	0.0	0.0	0.0	0.0
Poplar	200	50	3.7	5.2	6.5	8.8
Poplar	200	100	0.2	0.4	0.5	1.4
Poplar	600	50	5.1	8.3	10.3	12.9
Poplar	600	100	2.9	5.2	7.1	9.9
Willow	50	50	1.7	2.6	3.2	4.0
Willow	50	100	0.3	0.5	0.6	0.7
Willow	200	50	3.0	5.1	6.1	7.4
Willow	200	100	3.6	5.1	6.2	7.0
Willow	600	50	4.3	7.3	8.9	11.2
Willow	600	100	4.7	7.5	9.0	10.8
SEM (S*L*D)			0.16	0.25	0.32	0.38
Variance:			Probability			
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem length (L)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*L			**0.0367**	**0.0114**	**0.0009**	**0.0005**
S*D			**0.0001**	**0.0001**	**0.0001**	**0.0009**
S*L*D			**0.0001**	**0.0001**	**0.0001**	**0.0001**

SEM : standard error of the least square means

5.3.5.4 Canopy diameter

5.3.5.4.1 Inter-row canopy diameter

There was a significant (P=0.0001) interaction between species, stem length and planting depth on inter-row canopy diameter, during the measurement dates (Table 5.6). For example at 190 DAP, willow of 600 mm (57 cm vs 41 cm), 200 mm (35 cm vs 23 cm) and 50 mm (14 cm vs 2 cm) stem lengths produced greater inter-row canopy diameter at 50 mm planting depth than 100 mm depth. A similar trend was observed on the other observation dates. Poplar stem lengths of 600 mm (36 cm vs 27 cm) and 200 mm (25 cm vs 4 cm) produced greater inter-row canopy diameter at 50 mm than 100 mm planting depth, but no significant difference was found between inter-row canopy of 50 mm stems planted at 50 and 100 mm depths (Table 5.6). A similar pattern was found for the other dates of measurement.

Willow had greater (P=0.0001) inter-row canopy diameter than poplar. For example at 190 DAP, greater inter-row canopy diameter was observed for willow than poplar with means of 29 cm and 15 cm, respectively. The 600 mm stems produced a greater (P=0.0001) inter-row canopy diameter than the shorter stems. At 190 DAP, stem length of 600 mm produced greater inter-row canopy diameter than 200 mm and 50 mm stem lengths (40 cm > 22 cm > 4 cm, respectively). Planting depth significantly (P=0.0001) affected inter-row canopy at all times. Inter-row canopy diameter was greater for 50 mm than 100 mm planting depths at 190 DAP (29 cm vs 16 cm, respectively).

5.3.5.4.2 In-row canopy diameter

In-row canopy diameter was affected by the interaction (P=0.0001) of species, stem length and planting depth at 190 DAP (Table 5.7). Willow of 600 mm (69 cm vs 48 cm), 200 mm (34 cm vs 23 cm) and 50 mm stem lengths (13 cm vs2 cm) produced greater in-row canopy diameter when planted at a 50 mm compared with 100 mm depth. A similar result was found for 600 mm and 200 mm stem lengths of poplar, but not for 50 mm stem length where planting at 50 mm and 100 mm planting depths produced the same in-row canopy diameter (Table 5.7).

Willow produced greater (P=0.0001) in-row canopy diameter than poplar (32 cm vs 18 cm, respectively) at 190 DAP (Table 5.7). Stem length of 600 mm produced greater in-row canopy diameter than 200 mm and 50 mm stem lengths with means of 50 cm > 21 cm > 4 cm, respectively. Planting depth significantly (P=0.0001) affected in-row canopy diameter with trees established from planting at 50 mm depth showing twice the canopy diameter of those from the 100 mm planting depth (34 cm vs 17 cm, respectively).

Table 5.6 Effect of horizontal planting at two depths of willow and poplar of three stem lengths on inter-row canopy diameter.

Treatments			Inter-row canopy diameter (cm)			
Species	Stem length (mm)	Planting depth (mm)	Days after planting			
			90	130	160	190
Poplar	50	50	0	0	0	0
Poplar	50	100	0	0	0	0
Poplar	200	50	12	20	23	25
Poplar	200	100	1	1	2	4
Poplar	600	50	21	27	33	36
Poplar	600	100	6	18	20	27
Willow	50	50	6	12	12	14
Willow	50	100	1	2	2	2
Willow	200	50	14	28	32	35
Willow	200	100	11	18	21	23
Willow	600	50	22	41	49	57
Willow	600	100	19	35	39	41
SEM (S*L*D)			0.5	1.0	1.1	1.2
Variable:			Probability			
Species (S)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Stem length (L)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
Planting depth (D)			**0.0001**	**0.0001**	**0.0001**	**0.0001**
S*L			**0.0047**	**0.0001**	**0.0001**	**0.0002**
S*D			**0.0001**	0.5789	0.9874	0.0572
S*L*D			**0.0001**	**0.0001**	**0.0001**	**0.0001**

SEM : standard error of the least square means

Table 5.7 Effect of horizontal planting at two depths of willow and poplar of three stem lengths on in-row canopy diameter.

Treatments			In-row canopy diameter (cm)
Species	Stem length (mm)	Planting depth (mm)	190 days after planting
Poplar	50	50	0
Poplar	50	100	0
Poplar	200	50	25
Poplar	200	100	4
Poplar	600	50	55
Poplar	600	100	28
Willow	50	50	13
Willow	50	100	2
Willow	200	50	34
Willow	200	100	23
Willow	600	50	69
Willow	600	100	48
SEM (S*L*D)			1.5
Variable:			Probability
Species (S)			**0.0001**
Stem length (L)			**0.0001**
Planting depth (D)			**0.0001**
S*L			**0.0068**
S*D			0.7984
S*L*D			**0.0001**

SEM : standard error of the least square means

5.3.6 Effect of stem length and horizontal planting depth on above-ground biomass production

5.3.6.1 Above-ground biomass

5.3.6.1.1 Edible DM

No significant interaction effects on edible DM were found (Table 5.8). There were significant ($P < 0.05$) species, stem length and planting depth effects on edible DM at 150 DAP. Willow produced higher edible DM than poplar (12 g/tree vs 7 g/tree). Stems of 600 mm length produced higher edible DM than 200 mm and 50 mm stem lengths (19 g/tree > 8 g/tree > 0.2 g/tree, respectively). Planting at 50 mm depth produced higher edible DM than planting at 100 mm depth with means of 12 g/tree and 6 g/tree, respectively (Table 5.8).

Stem length significantly (P=0.0001) affected edible DM at 229 DAP with 600 mm material producing higher edible DM than 200 mm and 50 mm stem lengths (58 g/tree > 19 g/tree > 2 g/tree, respectively). There were no other significant effects at this time (Table 5.8).

Table 5.8 Effect on edible dry matter of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Edible DM per tree (g/tree)	
Species	Stem length (mm)	Planting depth (mm)	Days after planting 150	229
Poplar	50	50	0	0
Poplar	50	100	0	0
Poplar	200	50	11	37
Poplar	200	100	0	18
Poplar	600	50	23	50
Poplar	600	100	7	58
Willow	50	50	1	3
Willow	50	100	0	5
Willow	200	50	14	15
Willow	200	100	7	8
Willow	600	50	26	77
Willow	600	100	21	49
SEM (S*L*D)			3.3	9.9
Variable:			Probability	
Species (S)			**0.0227**	0.8570
Cutting length (L)			**0.0001**	**0.0001**
Planting depth (D)			**0.0024**	0.2002
S*L			0.2523	0.1942
S*D			0.2406	0.5376
S*L*D			0.1874	0.3584

SEM : standard error of the least square means

5.3.6.1.2 Total shoot DM

Total shoot DM was affected by the interactions between species and stem length, and species and planting depth, at 150 DAP (Table 5.9). Trees established from 600 mm willow stem lengths (186 g/tree) produced higher total shoot DM than those from 200 mm (59 g/tree) and 50 mm stem lengths (5 g/tree). Poplar also produced higher shoot DM from longer stems (600 mm) than 200 mm and 50 mm stems with means of 114 g/tree > 30 g/tree = 0 g/tree, respectively. Poplar stems planted at 50 mm depth produced higher total shoot DM than when planted at 100 mm depth (73 g/tree vs 45 g/tree, respectively), whereas no significant difference in shoot DM was found for willow planted at

different depths (Table 5.9). No significant interactions effects on total shoot DM were found at 229 DAP (Table 5.9).

Species and stem length significantly (P < 0.001) affected total shoot DM at 150 DAP. Willow produced higher total shoot DM than poplar (83 g/tree vs 48 g/tree). Stem lengths of 600 mm produced higher edible DM than 200 mm and 50 mm stem lengths with means of 150 g/tree, 44 g/tree and 3 g/tree, respectively. Planting depth had no effect on total shoot DM (Table 5.9).

Stem length significantly (P=0.0001) affected edible DM at 229 DAP with lengths of 600 mm producing higher edible DM than 200 mm and 50 mm stem lengths (290 g/tree > 90 g/tree > 5 g/tree, respectively). Species and planting depth had no significant effects on total shoot DM at 229 DAP (Table 5.9).

Table 5.9 Effect on total shoot dry matter (DM) of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Total shoot DM per tree (g/tree)	
Species	Stem length (mm)	Planting depth (mm)	Days after planting 150	229
Poplar	50	50	0	0
Poplar	50	100	0	0
Poplar	200	50	59	136
Poplar	200	100	0	84
Poplar	600	50	161	226
Poplar	600	100	67	350
Willow	50	50	10	15
Willow	50	100	0	13
Willow	200	50	56	81
Willow	200	100	62	60
Willow	600	50	163	343
Willow	600	100	209	239
SEM (S*L*D)			16.9	31.4
Variable:			Probability	
Species (S)			**0.0015**	0.6898
Stem length (L)			**0.0001**	**0.0001**
Planting depth (D)			0.0709	0.6251
S*L			**0.0324**	0.4616
S*D			**0.0032**	0.0820
S*L*D			0.0583	0.0501

SEM : standard error of the least square means

5.3.6.2 Below-ground biomass

5.3.6.2.1 Root number

There were significant ($P < 0.001$) interactions between species and stem length at 150 DAP and 229 DAP, and between species, stem length and planting depth on root number at 229 DAP (Table 5.10). For example at 229 DAP, willow established from 600 mm stem lengths produced higher root number at 100 mm than 50 mm planting depth (160 g/tree vs 101 g/tree), whereas no significant differences in root number were observed between 200 mm and 50 mm stem lengths and planting depths of 50 and 100 mm.

Species ($P< 0.001$) and stem length ($P < 0.001$) significantly affected root number at 150 and 229 DAP. There was a significant difference in root number at each planting depth at 229 DAP. For example at 229 DAP, willow produced higher root number than poplar (61 vs 15). Stem lengths of 600 mm produced higher root number than 200 mm and 50 mm stem lengths with means of 82 > 26 > 6, respectively (Photos 5.1 & 5.2). Planting at 100 mm depth produced higher root number than planting at 50 mm depth with means of 46 and 31, respectively (Table 5.10).

Table 5.10 Effect on root number of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Root no per tree	
Species	Stem length (mm)	Planting depth (mm)	Days after planting 150	229
Poplar	50	50	0	0
Poplar	50	100	0	0
Poplar	200	50	9	10
Poplar	200	100	0	16
Poplar	600	50	17	19
Poplar	600	100	5	47
Willow	50	50	2	13
Willow	50	100	0	11
Willow	200	50	42	40
Willow	200	100	42	39
Willow	600	50	69	101
Willow	600	100	108	160
SEM (S*L*D)			15.8	7.1
Variable:			Probability	
Species (S)			**0.0003**	**0.0001**
Stem length (L)			**0.0009**	**0.0001**
Planting depth (D)			0.7754	**0.0013**
S*L			**0.0094**	**0.0001**
S*D			0.3086	0.3935
S*L*D			0.6947	**0.0007**

SEM : standard error of the least square means

Photo 5.1 Root growth of willow from stem lengths of 600 mm (TRT. 7 and 11), 200 mm (TRT. 12 and 5) and 50 mm (TRT. 6 and 1), planted at two depths.

Photo 5.2 Root growth of poplar from stem lengths of 600 mm (TRT. 4 and 2) and 200 mm (TRT. 8 and 10), planted at two depths.

5.3.6.2.2 Root length

There was an interaction (P=0.0002) between species and stem length on total root length at 229 DAP (Table 5.11). No significant effects were observed for the other treatment interactions at 229 DAP or for any interactions at 150 DAP.

Species and stem length had significant effects on total root length at each time (P < 0.001). For example, at 229 DAP willow produced greater total root length than poplar (506 cm vs 212 cm, respectively). Stem lengths of 600 mm produced greater total root length (774 cm) than 200 mm and 50 mm stem lengths (258 cm and 45 cm, respectively). Planting depth had no effect on root length.

Table 5.11 Effect on total root length of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Total root length per tree (cm/tree)	
Species	Stem length	Planting depth	Days after planting	
	(mm)	(cm)	150	229
Poplar	50	50	0	0
Poplar	50	100	0	0
Poplar	200	50	69	169
Poplar	200	100	0	259
Poplar	600	50	176	332
Poplar	600	100	197	513
Willow	50	50	20	83
Willow	50	100	0	96
Willow	200	50	241	321
Willow	200	100	220	285
Willow	600	50	532	1079
Willow	600	100	534	1174
SEM (S*L*D)			103.9	98.33
Variable:			Probability	
Species (S)			**0.0056**	**0.0001**
Stem length (L)			**0.0003**	**0.0001**
Planting depth (D)			0.8092	0.324
S*L			0.0935	**0.0002**
S*D			0.9804	0.5657
S*L*D			0.9938	0.8587

SEM : standard error of the least square means

5.3.6.2.3 Root volume

No significant interaction effects on root volume were found (Table 5.12). Species, stem length and planting depth significantly ($P < 0.05$) affected root volume at 150 DAP. Willow produced twice the root volume of poplar (2 cm^3/tree vs 1 cm^3/tree). Long stem (600 mm) produced higher root volume than 200 mm and 50 mm stem lengths (3 cm^3/tree > 1.6 cm^3/tree > 0.03 cm^3/tree, respectively). Planting at 50 mm depth produced higher root volume than planting at 100 mm depth with means of 2 cm^3/tree and 1 cm^3/tree, respectively.

At 229 DAP, stem length had significant effect on root volume with 600 mm stem length producing higher root volume than 50 mm stem length (29 cm^3/tree vs 0.7 cm^3/tree).

Table 5.12 Effect on root volume of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Root volume per tree (cm^3/tree)	
Species	Stem length	Planting depth	Days after planting	
	(mm)	(mm)	150	229
Poplar	50	50	0	0
Poplar	50	100	0	0
Poplar	200	50	2	46
Poplar	200	100	0	13
Poplar	600	50	3	39
Poplar	600	100	1	28
Willow	50	50	0	1
Willow	50	100	0	2
Willow	200	50	3	7
Willow	200	100	2	6
Willow	600	50	6	34
Willow	600	100	4	16
SEM (S*L*D)			1.0	13.9
Variable:			Probability	
Species (S)			**0.0159**	0.2243
Stem length (L)			**0.0004**	**0.0272**
Planting depth (D)			**0.0346**	0.2131
S*L			0.1579	0.4612
S*D			0.8879	0.6026
S*L*D			0.5536	0.7203

SEM : standard error of the least square means

5.3.6.2.4 Root dry matter(DM)

No significant interaction effects on root DM were found (Table 5.13). Stem length and planting depth had significant ($P < 0.05$) effects on root DM at 150 DAP (Table 5.13). Stem length of 600 mm produced higher root DM than 200 mm and 50 mm lengths (1.4 g/tree > 0.6 g/tree > 0.03 g/tree, respectively). Higher root DM was found for 50 mm than for 100 mm planting depth (0.9 g/tree vs 0.5 g/tree). Root DM production of willow and poplar was similar.

At 229 DAP, stems 600 mm and 200 mm long produced higher root DM than 50 mm stem lengths with means of 13 g/tree = 6.7 g/tree > 0.3 g/tree, respectively. Species and planting depth had no effect on root DM (Table 5.13).

Table 5.13 Effect on root dry matter of horizontal planting at two depths and three stem lengths for willow and poplar.

Treatments			Root DM per tree (g/tree)	
Species	Stem length	Planting depth	Days after planting	
	(mm)	(mm)	150	229
Poplar	50	50	0.0	0.0
Poplar	50	100	0.0	0.0
Poplar	200	50	1.1	18.0
Poplar	200	100	0.0	5.0
Poplar	600	50	1.0	20.3
Poplar	600	100	1.1	13.5
Willow	50	50	0.1	0.3
Willow	50	100	0.0	0.7
Willow	200	50	0.9	2.4
Willow	200	100	0.5	1.5
Willow	600	50	2.3	13.6
Willow	600	100	1.3	6.0
SEM (S*L*D)			0.3	5.7
Variable:			Probability	
Species (S)			0.0916	0.1140
Stem length (L)			**0.0001**	**0.0128**
Planting depth (D)			**0.0201**	0.1683
S*L			0.2129	0.4363
S*D			0.7145	0.5557
S*L*D			0.1860	0.7542

SEM : standard error of the least square means

Based on the results of total shoot DM and root DM measured at 299 DAP in all plots, there was a strong relationship between root DM and total shoot DM of willow planted at 50 mm and 100 mm planting depths (Figure 5.2). Higher root DM, particularly from 600 mm stems produced higher total shoot DM. A similar trend was observed for poplar (Figure 5.2) with a positive relationship between root DM and total shoot DM.

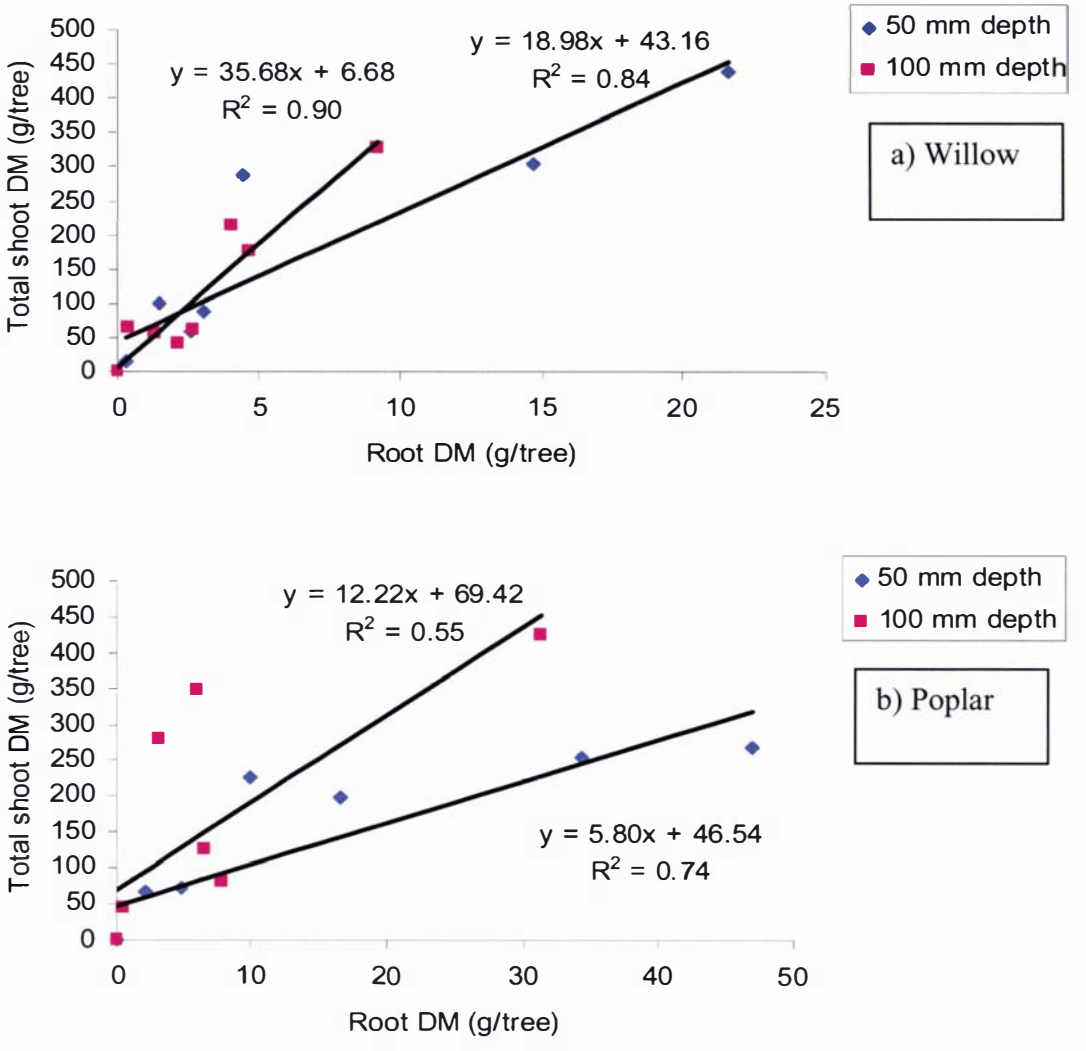

Figure 5.2 Relationship between total shoot DM and root DM for (a) willow (n= 9, P < 0.001) and (b) poplar, (n= 9, p < 0.05) at 50 mm and 100 mm planting depths (229 days after planting).

5.4 Discussion

5.4.1 Effect of horizontal planting depth on shoot emergence and tree survival of willow and poplar of different stem length.

Species, stem length and planting depth greatly influenced shoot emergence and tree survival. Long stems (600 mm) planted at a shallow depth of 50 mm had higher shoot emergence and tree survival than intermediate and short stems (50 mm), possibly because long stems have higher nutrient and carbohydrate reserves (Zierke 1994; Macpherson 1995; Hoag 2004). Short stems had lower root production which would have limited access to water and nutrients (Bowen 1981). Long stems have relatively high stem surface area with potential for a higher number of buds and greater shoot emergence. Buds are essential for good rooting and ideal growth of *Populus deltoides* (Coleman *et al.* 1993) and Bolleana poplar (Eggens *et al.* 1972).

Planting depth also plays an important role in determining shoot emergence and tree survival from horizontal planting. Higher shoot emergence and tree survival were found from 50 mm than 100 mm planting depth. This may be because shallow planting (50 mm) had improved soil aeration (O_2 level) compared to deep planting (100 mm), that influenced shoot growth and tree survival. Good aeration around the base of cuttings is important to ensure the formation of calluses and the production of roots at the bottom of cuttings. These factors lead to increased cambial activity, resulting in increasing respiration from the tissues (Zsuffa 1992) and root growth. Lower shoot emergence and tree survival were found from short stem cuttings (50 mm) of willow and poplar planted at 100 mm depth. This may because of low carbohydrate reserves in the small stems, aided by low aeration at 100 mm depth and low soil temperature, which resulted in low percentage of shoot emergence.

Stoltz (1968) found a positive correlation between total carbohydrate reserves and rooting mass of Chrysanthemum that influenced tree survival and growth. Failure of some trees on low temperature soil caused an insufficient root metabolism leading to deleterious effects such as inadequate supply of water and nutrients to the shoot (Lyr & Hoffmann 1967)

Adequate moisture is important during field planting as stem cuttings die easily and becomes desiccated if the weather is unfavourable. Higher survival rates for 600 mm and 200 mm stem lengths were aided by favourable weather conditions (Figure 4.1, Chapter 4). This was supported by Hathaway (1986) and Hudson (1997) who found the major limitations for establishment of willow are inadequate soil moisture and excessive weed competition. For 50 mm stem lengths, tree survival decreased from 42% (poplar) and 75% (willow) at 93 DAP (Table, 5.1) to 1% and 45%, respectively at 224 DAP (Table 5.2). A possible cause of this low tree survival rate was lack of rainfall from 1 January 2004 to 6 January 2004. Although 50 mm stems produced shoots, lack of root formation (Photo 5.3) for first the 150 DAP (Tables 5.12 and 5.I3) possibly caused tree death during periods of low soil moisture. Higher % survival from willow than poplar may be because willow produced twice the root volume of poplar within the first 150 DAP.

Weed control is also essential for horizontal stem planting. A frequent weed control schedule needs to be planned to ensure low weed competition for the first four months after planting especially when using short stems. According to Piggin *et al*. (1994) weed competition severely restricts seedling growth of tree species such as *Leucaena*, although seedlings are rarely killed by competition alone. Hand weeding and herbicide spraying on 25 October 2003 and 12 December 2003, respectively, combined with low nutrient reserves and lack of rainfall in early January 2004, were not adequate to prevent tree death, particularly those developed from short stems (50 mm).

Photo 5.3 Lack of root formation from 50 mm stem length resulted in death during unfavourable weather conditions.

5.4.2 Effect of horizontal planting of willow and poplar of different stem length and planting depth on tree growth and biomass production

The results indicated a significant advantage in tree growth from using 600 mm stem lengths compared with 200 mm and 50 mm stem lengths. Long stem (600 mm) of both willow and poplar produced higher shoot number, shoot length, and canopy diameter, and thicker shoots. This result was supported by the strong correlation between physical size of cutting and poplar growth (Bowersox 2001). Faster growth from long stems may be related to higher root production, which influences water and nutrient uptake for tree growth.

Willow and poplar established at 50 mm depth produced higher shoot growth (shoot length, shoot number and canopy diameter) than 100 mm depth. This may be because the shallower soil was richer in humus, had good soil aeration and higher soil temperature. These factors encourage vigorous root growth which is necessary for shoot growth. FAO (1979), found that good soil aeration is essential for successful poplar cultivation. Willow produced higher shoot growth than poplar at 100 mm planting depth, most likely due to greater bud initiation and shoot growth by willow than poplar.

There was a significant advantage from using 600 mm stem lengths as planting stock where growing conditions were favourable (2003/2004). Total shoot DM was related positively to root DM of willow and poplar (Figure 5.4). This was

supported by Heilman *et al.* (1994) who found significant relationships between above-ground weights and weights of first-order roots of hybrid poplar (*Populus trichocarpa x P. deltoides)*. Long stems (600 mm) produced higher edible DM and total shoot DM than short stems (50 mm). This may be because long stems produced higher root DM and higher shoot growth, leading to higher edible and total biomass compared to short stem cuttings. Another reason may be that long stems have large nutrient and carbohydrate reserves (Zierke 1994; Macpherson 1995) to support early root and shoot growth.

In terms of total shoot DM, 600 mm stem lengths produced 2900 kg DM/ha (290 g DM/tree) compared to only 50 kg DM/ha (5 g DM/tree) from 50 mm stem cuttings when adjusted to 100% tree survival. Higher biomass production from long stems was in agreement with Douglas *et al.* (2003) who found higher total yield of willow from 2 m than 1.1 m stem cuttings when planted vertically.

Long stems (600 mm) of willow planted horizontally produced total shoot DM of 2910 kg DM/ha (291 g DM/tree) and edible DM of 630 kg DM/ha (63 g DM/tree) these were less than vertical planting which produced 5810 kg DM/ha (581 g DM/tree) and 1130 kg DM/ha (113 g DM/tree) for total and edible DM, respectively (Experiment 2- Chapter 4). The edible biomass of 1130 kg DM/ha was not much different from that of Douglas *et al.* (1996), who measured 1200 kg DM/ha in a vertical planting. Higher edible (1560 kg DM/ha vs 540 kg DM/ha) and total shoot DM (7280 kg DM/ha vs 2880 kg DM/ha) of poplar planted vertically rather than horizontally indicated that vertical planting produced higher edible and total shoot DM in a fodder block in the establishment year.

The purpose of including 50 mm stem lengths was to reduce the cost of planting material during field establishment. Promising results from long and intermediate stems (600 mm and 200 mm) in terms of growth, and edible and total shoot DM, may compensate for the extra start-up cost during field establishment. However, the cost of using 600 mm stem lengths may be three to six times higher than for 200 mm and 50 mm stem lengths. Plant materials used in this trial were unwanted for conservation plantings and were going to be

discarded. This study showed that the material was valuable for establishing fodder blocks.

5.5 Conclusion

Stems of 600 mm and 200 mm length, planted at 50 mm depth, produced higher shoot emergence, tree survival and tree growth (shoot number, shoot length, shoot diameter, canopy diameter) than stems of 50 mm length planted at the same depth. Willow had earlier shoot emergence, higher tree survival and better shoot growth than poplar.

Long stems (600 mm) produced higher edible and total shoot DM than intermediate (200 mm) and short stems (50 mm). Higher shoot growth and above-ground biomass production from long stems (600 mm) was linked to greater root production (root number, root length and root DM).

It is recommended that farmers establishing willow and poplar in horizontal plantings for fodder plant long stems (200 mm to 600 mm) for higher tree growth, biomass production and cost effectiveness.

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6 Effect of pasture management on soil water and stem water potential of willow in a willow-pasture system.

CONTENT

6. 1 Introduction

Successful establishment of willow and poplar from previous research in Chapters 3, 4 and 5, clearly indicated that soil moisture was the single most limiting factor influencing tree survival and growth. Poplar (*Populus* spp.) (Braatne *et al.* 1992) and willow (*Salix* spp.) are sensitive to water stress, particularly young trees (Chapter 3). Thus it is crucial to determine the water demands and how water uptake influences willow and poplar growth. Water stress also reduces growth in other plant species (Boyer 1968; Eastham *et al.* 1989). Thus early detection of water stress is important for the successful establishment and growth of many plant species on farms.

Water tension within the tree is due to internal water stress resulting from leaf transpiration and the failure of the tree to acquire water quickly enough to balance the water loss from the leaves (Waring & Cleary 1967). Hall *et al.* (1998) found under well-watered conditions that transpiration of short rotation crops (SRC) of poplar (*Populus deltoides* x *trichocarpa*) and willow (*Salix burjatica*) reached a peak of almost 11 mm/day/tree. As water stress increased through the dry summer, the transpiration ratio (transpiration/reference evapotranspiration) decreased to almost zero (Ybalmea *et al.* 2000; Anon 2001). However, knowledge of water depleted or conserved under willow-pasture agroforestry is limited.

Soil water and tree water status in the field have usually been assessed using soil volumetric water content (Barker *et al.* 1985) and stem/leaf water potential (Jackson 1974; Burghardt & Riederer 2003). Soil volumetric water content is used to measure soil water deficits (SWD). SWD is defined as the amount of water which must be added to restore the soil moisture to field capacity and is calculated as depletion of total water storage below field capacity (Barker *et al.* 1985). Tree growth occurs when water balance within plants is favourable or in a period of low negative plant water potential (Vazquez *et al.* 1997). To measure water status in plant tissues, stem/leaf water potential can be measured using a pressure bomb (Shackel & Gross 2002). It is a useful instrument to detect whether or not trees are under water stress. Data from

leaf/stem water potential can be correlated to soil water availability/deficit to estimate requirements for water.

In agroforestry, the main below-ground competition is for soil moisture and nutrients (Sharrow 1999). There is an impact of understorey pasture on young conifers particularly during the dry season (Nambiar & Zed 1980). Once the tree roots have established well under the pasture root zone, tree growth is less influenced by the effect of pasture on soil moisture (Sharrow 1999). However, little research has been conducted on the effect of understorey pasture management on soil moisture and tree water potential in a willow-pasture agroforestry system. Therefore, the objectives of this experiment were (i) to determine the effect of three pasture managements on soil water (soil water content, soil water loss and deficit) beneath willow in a willow-pasture system and (ii) to determine the effect of pasture management on stem water potential of willow in a willow-pasture system.

6.2 Materials and methods

6.2.1 Experimental site

The experiment was conducted at the Pasture and Crop Unit, Moginie, Massey University, Palmerston North, situated about 5 km from Palmerston North city (longitude 175^{o} 37' E, latitude 40^{o} 21' S, altitude 30 m above sea level). The soil type was Tokomaru silt loam with an aeric fragiaqualf (gleyed yellow-grey earth) for which detailed morphological and physical data is given by Scotter *et al*. (1979). Rainfall data during the growing season (2004/2005) were obtained from AgResearch Grasslands, Palmerston North, 2.5 km from the experimental site.

6.2.2 Experimental treatments and design

Willow trees were selected from trees established on 5 September 2002 (3 years old). The trees were established using stem cuttings 600 mm long with stem diameters ranging from 10 mm to 40 mm. Stem cuttings were planted at 1.2 m x 1.2 m spacing giving 6944 trees/ha. The treatments were three pasture

managements: (i) Grazing – monthly (started on 6 November 2004), (ii) Herbicide: sprayed twice per season - (a) Gallant NF at rate 3 l/ha (0.25 kg a.i. ha^{-1} haloxyfop (R-Isomer) and 0.87 kg a.i. ha-1 diethylene glycol) and Versatill, at 1.0 l/ha (300 g clopyralid/l) on 23 September 2004) and (b) Buster at rate 7.5 l/ha (200 g/l glufosinate-ammonium) on 19 October 2004, (iii) Control - no weed control. The treatments were arranged in three randomised complete blocks. Each plot was 2.4 m x 9.6 m (24 trees/plot).

6.2.3 Measurements

6.2.3.1 Herbage mass

Herbage mass of pasture under the spaced willows was determined by harvesting monthly according to the treatment. All material was washed and then oven-dried at 80 ^{o}C for at least 24 hours. Three samples per treatment were harvested randomly by cutting pasture in 0.1 m^2 quadrats to the ground level.

6.2.3.2 Total root density

Roots were sampled on 16-17 February 2005 using the coring method at 150 mm, 300 mm and 600 mm distance from a willow tree at 0-150 mm, 150-300 mm and 300-450 mm soil depths, but samples were taken for only one side (west side) of the tree. Total root density (TRD) was calculated as: TRD = root weight (willow and pasture) (g DM)/ soil volume ($\pi r^2 h$) where π = 3.14, r (core radius) = 2.25 cm, h = soil depth.

6.2.3.3 Soil water content

Soil water content was measured using Time Domain Reflectometry (TDR) (Parchomchuki *et al.* 1997) four times per month (Photo 6.1). A total of 162 sets (3 pasture managements x 3 distances from trees x 3 soil depths x 2 trees/plot x 3 replicates) of permanent TDR probes were installed at 150 mm, 300 mm and 600 mm away from the willow trees at three soil depths: 0-150 mm, 0-300 mm and 0-450 mm.

6.2.3.4 Soil water loss/recharge per day

Soil water loss/recharge per day per tree was calculated from the difference in SWC (measured in day 2 and day 1) measured 300 mm from willow trees at 150 mm, 300 mm and 450 mm soil depths. Soil water loss/recharge = $(\Theta_2 - \Theta_1)/100 \times h$ where Θ_1 = SWC day 1, Θ_2 = SWC day 2, h = soil depth.

Photo 6.1 Soil water content measurement using Time Domain Reflectometry.

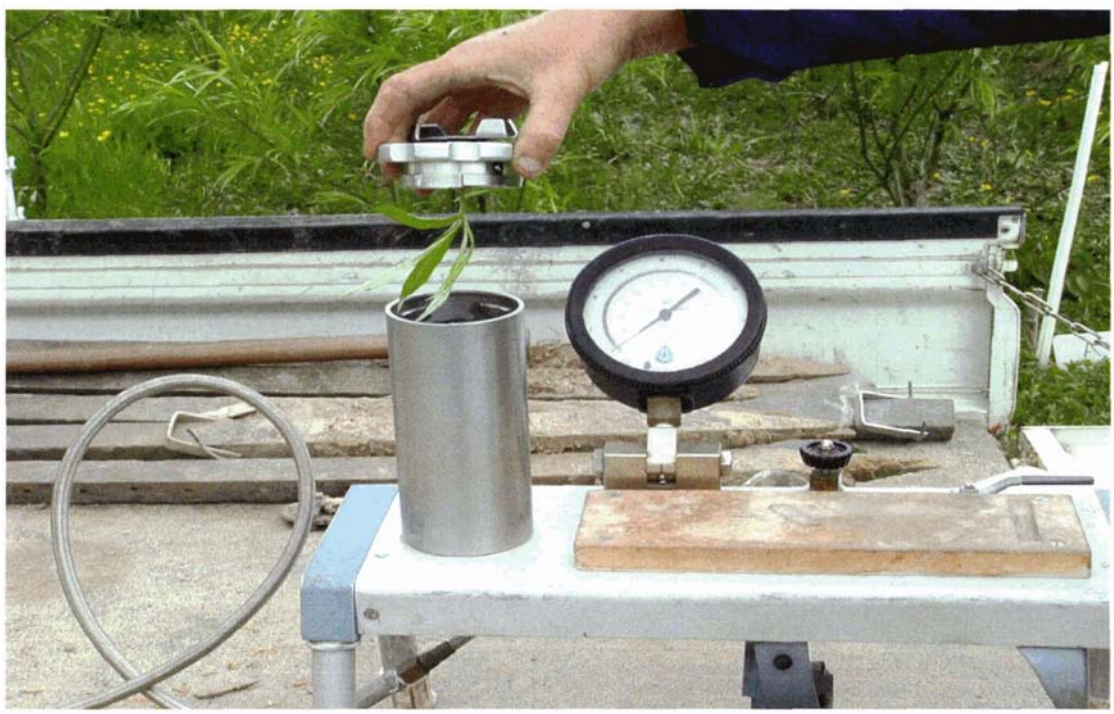
6.2.3.5 Soil water deficit to field capacity

Soil water deficit was estimated from the difference between volumetric SWC at field capacity and volumetric SWC measured at three soil depths of 0-150 mm, 0-300 mm and 0-450 mm, 300 mm away from the trees. Soil moisture at field capacity for a Tokomaru silt loam was 0.44cm^3/cm^3 at 150 mm depth, 0.39 cm^3/cm^3 at 300 mm depth and 0.39 cm^3/ cm^3 at 450 mm soil depth (Scotter *et al*. 1979).

6.2.3.6 Stem water potential

A pressure bomb was used to measure stem/leaf water potential twice a month (Photo 6.2). Twelve small stems (2-3 mm diameter) with leaves were collected randomly from six willow trees per treatment or 2 stems per tree and placed in the pressure bomb with its stem locked into the cylinder of the pressure bomb. Pressure of nitrogen gas was applied to the tissue until water just appeared at the cut end of the stem. When water appeared, the pressure applied to the tissue was equal to the leaf water potential (Campbell 2004).

Photo 6.2 Measurement of stem water potential using a pressure bomb.



6.2.4 Statistical analysis

All data were analysed with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS 2001). Repeated measures analysis of variance (ANOVA) were conducted on SWC, soil water loss/recharge per day, water deficit to field capacity and stem water potential to determine the effect of pasture management treatments on overall mean SWC. A regression analysis was conducted to determine the relationship between (i) soil water content (300 mm from tree at 0-150 mm, 0-300 mm and 0-450 mm soil depths) and stem water potential and (ii) stem water potential and soil water deficit (300 mm from tree at 0-150 mm, 0-300 mm and 0-450 mm soil depths) to predict water requirement. The level of significance was tested at 5%.

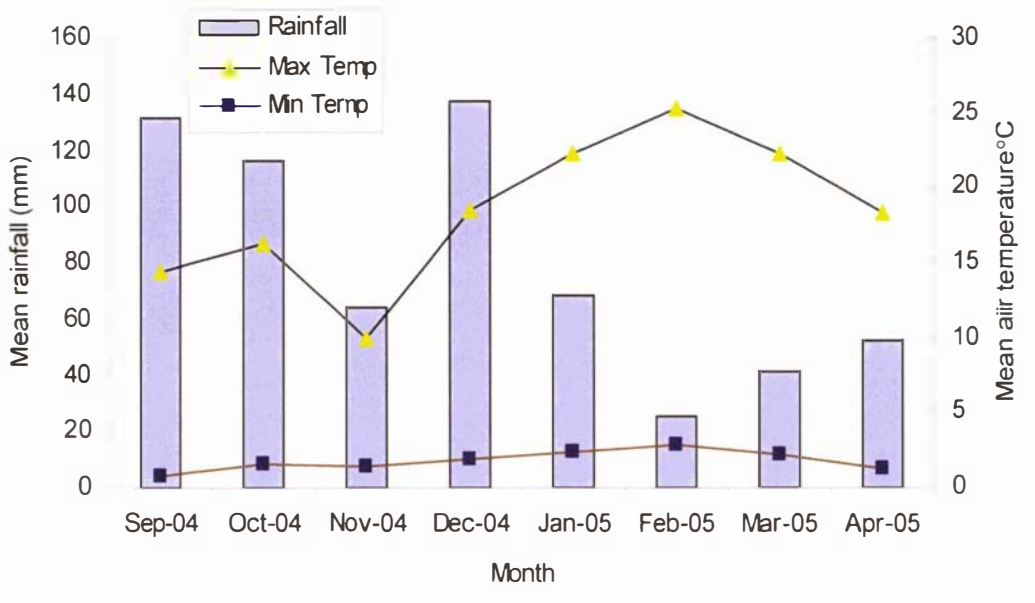
6.3 Results

6.3.1 Rainfall and temperature

The total rainfall during the eight-month growing season (2004/2005) was 634 mm (Figure 6.1), with rainfall during summer being 137 mm in December 2004, 68 mm in January 2005 and 25 mm in February 2005.

The mean maximum and minimum temperatures during the experiment were 18.4 °C and 10.0 °C, respectively (Figure 6.1). The maximum temperatures during summer were 18.5 °C in December 2004, 22.2 °C in January 2005 and 25.2 °C in February 2005. The minimum temperature ranged from 9.9 °C to 15.4 °C in summer (Figure 6.1).

Figure 6.1 Mean rainfall and air temperature at Palmerston North during the 2004/2005 growing season.



6.3.2 Pasture herbage mass of variously managed pasture beneath spaced willow

Pasture management had a significant effect ($P < 0.05$) on pasture herbage mass, except on 22 November 2004 (Table 6.1). For example on 21.October 2004, the grazing and control (no weed control) treatments had higher herbage mass than the herbicide treatment (2253 kg/ha=2220 kg/ha > 767 kg/ha, respectively). Grazing treatment and control resulted in similar herbage mass production as grazing plots did not have any treatment until 6 November 2004 when the grazing treatment started. Grazing was not implemented because the willows were starting to produce new shoots. On 24 March 2005 the control had higher herbage mass than the grazing and herbicide treatments (5946 kg/ha > 2586 kg/ha > 0 kg/ha, respectively). The results indicated that higher understorey competition was likely from the control treatment than the grazing and herbicide treatments.

Table 6.1 Herbage mass of pasture beneath spaced willows managed in three pastures managements.

Pasture management	Pasture herbage mass (kg DM/ha)						
	21.10.04	22.11.04	21.12.04	20.1.05	25.2.05	24.03.05	24.4.05
Grazing	2253	2241	2357	1773	3997	2586	3170
Herbicide	767	406	0	0	0	0	37
Control	2220	3978	9677	7300	4383	5946	6143
LSD (5 %)	1253	2897	4977	2772	6430	3311	2883
Probability	0.049	0.065	0.014	0.004	0.227	0.019	0.017

Note: Control – no weed control
Herbage mass includes dead materials.

6.3.3 Effect of understorey pasture management on total root density of willow and pasture

6.3.3.1 0-150 mm soil depth

Total root density was similar for all pasture management treatments at 150 mm ($P = 0.3422$), 300 mm ($P = 0.4818$), and 600 mm ($P = 0.6483$) distances from willow trees (Table 6.2). The total root density ranged from 0.0027 to 0.0045 g

DM/cm^3 for 150 mm, 0.0050 to 0.0040 g DM/cm^3 for 300 mm and 0.0024 to 0.0037 g DM/cm^3 for 600 mm distances from willow trees.

Table 6.2 Total root density measured at 0-150 mm soil depth and 150 mm, 300 mm and 600 mm distances from trees on 16 - 17 February 2005.

Pasture management	Total root density of willow and pasture (g DM/cm^3)		
	Distance from tree (mm)		
	150	300	600
Grazing	0.0027	0.0050	0.0037
Herbicide	0.0027	0.0020	0.0024
Control	0.0045	0.0040	0.0032
Mean	0.0030	0.0040	0.0030
LSD (5 %)	0.0036	0.0060	0.0041
Probability	0.3422	0.4818	0.6483

6.3.3.2 150-300 mm soil depth

Total root density was similar for all pasture management treatments at 150 mm (P = 0.3821), 300 mm (P = 0.2338) and 600 mm (P = 0.5887) distance from the tree (Table 6.3). It ranged from 0.0009 to 0.0013 g DM/cm^3 for 150 mm, 0.0005 to 0.0030 g DM/cm^3 and 0.0007 to 0.0011 g DM/cm^3 for 300 mm and 600 mm distances from willow trees, respectively (Table 6.3).

Table 6.3 Total root density measured at 0-150 mm soil depth and 150 mm, 300 mm and 600 mm distances from trees on 16 - 17 February 2005.

Pasture management	Total root density of willow and pasture (g DM/cm^3)		
	Distance from tree (mm)		
	150	300	600
Grazing	0.0012	0.0030	0.0011
Herbicide	0.0009	0.0005	0.0007
Control	0.0013	0.0010	0.0011
Mean	0.0010	0.0020	0.0010
LSD (5 %)	0.0008	0.0030	0.0014
Probability	0.3821	0.2338	0.5887

6.3.3.3 300-450 mm soil depth

Total root density of willow and understorey pasture was not affected by pasture management treatments at 150 mm (P = 0.2928), 300 mm (P = 0.2256) and 600 mm (P = 0.3977) distances from trees (Table 6.4). It ranged from 0.0007 to 0.0047 g/cm^3 for 150 mm, 0.0004 to 0.0006 g/cm^3 for 300 mm and 0.0007 to 0.0010 g/cm^3 for 600 mm distances from willow trees (Table 6.4).

Table 6.4 Total root density measured at 300-450 mm soil depth and 150 mm, 300 mm and 600 mm distance from tree on 16 -17 February 2005.

Pasture management	Total root density of willow and pasture (g/cm^3)		
	Distance from tree (mm)		
	150	300	600
Grazing	0.0047	0.0004	0.0010
Herbicide	0.0007	0.0004	0.0007
Control	0.0008	0.0006	0.0007
Mean	0.0020	0.0005	0.0008
LSD (5 %)	0.0056	0.0002	0.0005
Probability	0.2928	0.2256	0.3977

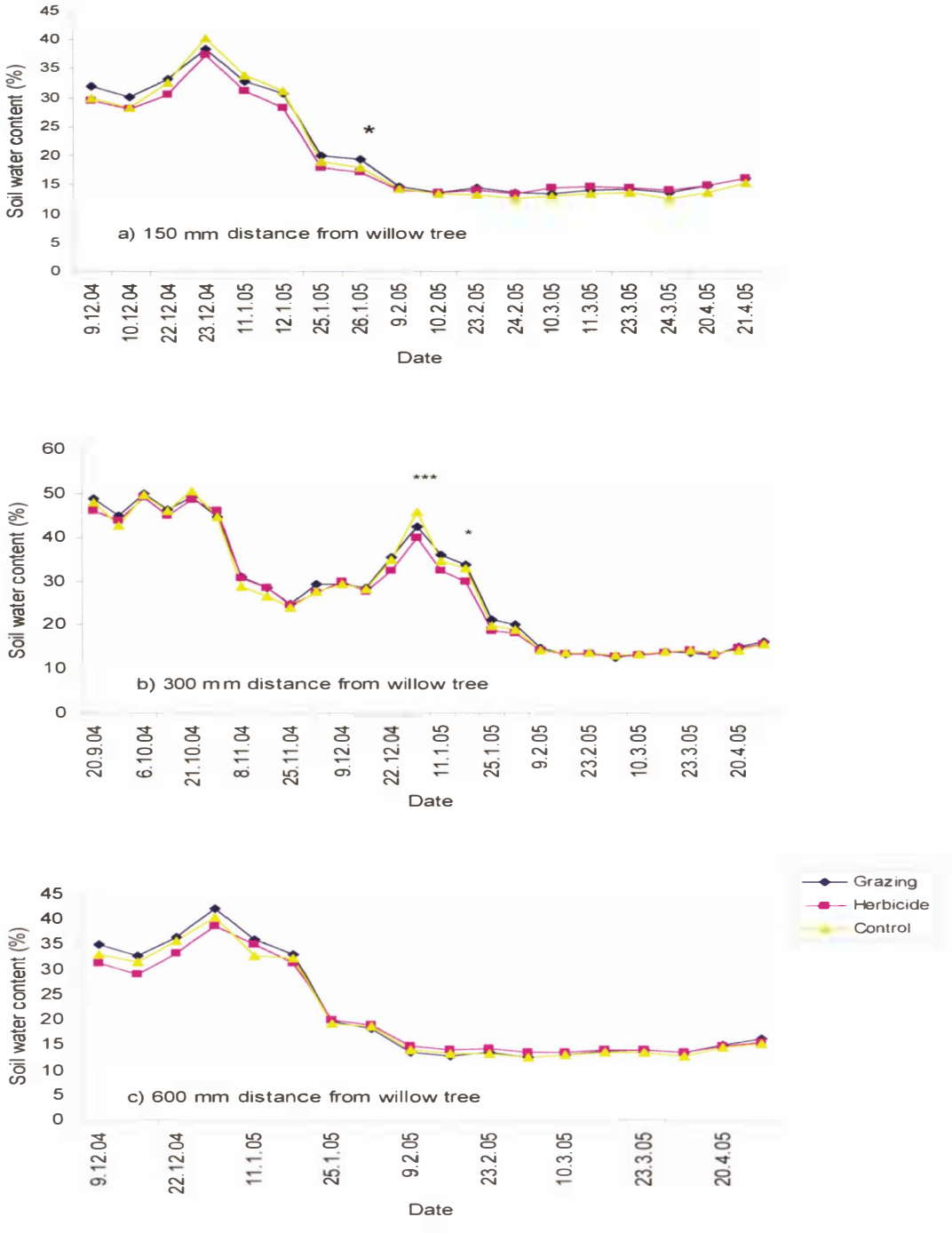
6.3.4 Treatment effects on soil water content

6.3.4.1 0-150 mm soil depth

Significant differences in soil water content (SWC) between pasture management treatments were observed on a few dates during December 2004 and January 2005 for 150 mm (26 January 2005) and 300 mm (23 December 2004 and 25 January 2005) from the willow trees, but not at 600 mm from willow trees (Figure 6.2). SWC was not affected by pasture management treatments on the other observation dates. For example on 26 January 2005 at 150 mm from willow trees (Figure 6.2), SWC was higher for the grazing and control treatments than herbicide treatment (19.5 % = 18.0 % > 17.2 %, respectively). Similarly on 12 January 2005 at 300 mm from willow trees, the grazing treatment had higher SWC than the herbicide treatment (33.7 > 29.9%, respectively), but was similar to the control treatment (33.7% = 32.9%, respectively).

Overall, there were significant differences between pasture management treatments in mean SWC at 150 mm ($P < 0.001$, LSD = 0.5), 300 mm ($P < 0.03$, LSD = 0.7) and 600 mm ($P < 0.01$, LSD = 0.6) distances from willow trees (Figure 6.2). At 150 mm from willow trees, the grazing treatment had higher mean SWC than control and herbicide treatments (21.1% > 20.4% = 20.2%, respectively). Control and grazing treatments had higher SWC than the herbicide treatment at 300 mm from willow trees (27.9% = 27.6% > 27.0%, respectively). Mean SWC at 600 mm from willow trees was higher for the grazing than the control and herbicide treatments (21.8% > 21.3% = 21.1%, respectively).

Figure 6.2 Effect of pasture management on volumetric soil water content at 0-150 mm soil depth.



Note: * indicates significant difference at 5 % level.

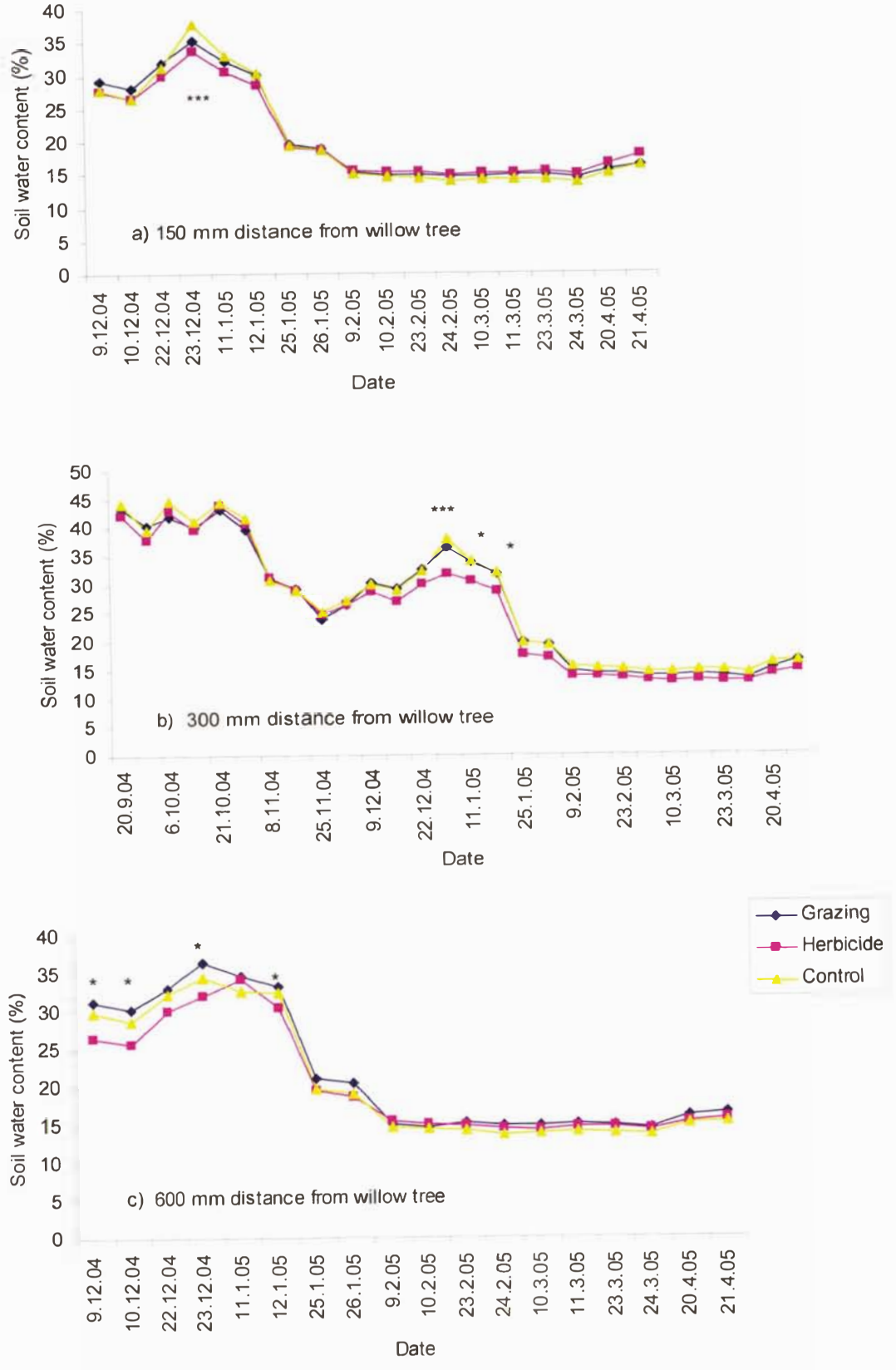
*** indicates highly significant at 5 % level.

6.3.4.2 0-300 mm soil depth

SWC was affected ($P < 0.05$) by pasture management at 150 mm (23 December 2004), 300 mm (23 December 2004, 11 January 2005 and 12 January 2005) and 600 mm (9 December 2004, 10 December 2004, 23 December 2004 and 12 January 2005) distances from willow trees (Figure 6.3). However, there were no significant effects at the other observation dates. For example, on 23 December 2004 at 150 mm from willow trees, the control treatment had higher SWC than grazing and herbicide treatments with means of 37.7% > 35.2% > 33.8%, respectively. The control and grazing treatments had higher SWC than the herbicide treatment (37.7% = 36.4% > 31.8%, respectively) at the same date at 300 mm from the willow trees. A similar result was found at 600 mm from willow trees on 9.December 2004, with the grazing and control treatments having higher SWC than the herbicide treatment (31.2% = 29.9% > 26.5%, respectively).

Overall, there were significant differences between pasture management treatments in mean SWC at 300 mm ($P < 0.0001$, LSD = 0.5) and 600 mm ($P < 0.0001$, LSD = 0.6) distances from willow trees. SWC was not affected by pasture management at 150 mm from willow trees. At 300 mm distances from willow trees, the control treatment had higher SWC than the grazing and herbicide treatments (26.9% > 26.2% > 25.1%, respectively). The grazing treatment had higher SWC than the control and herbicide treatments at 600 mm distance from willow trees (21.7% v/v > 20.8% v/v = 20.2% v/v, respectively).

Figure 6.3 Effect of pasture management on volumetric soil water content at 0 - 300 mm soil depth.

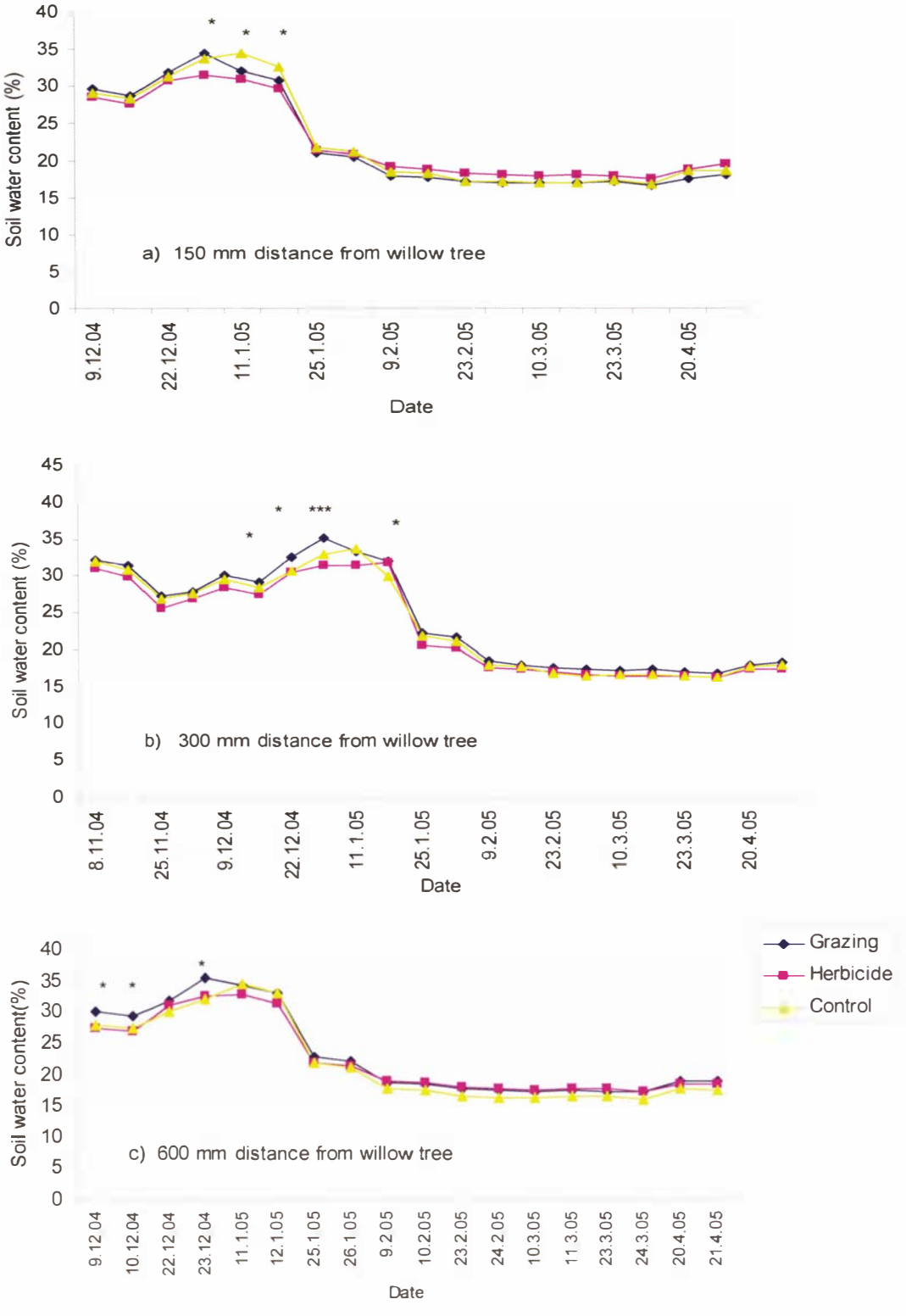


6.3.4.3 0-450 mm soil depth

There were significant differences in SWC ($P < 0.05$) for 0-450 mm soil depth between the pasture management treatments at 150 mm (23 December 2004, 11 January 2005 and 12 January 2005), 300 mm (10 December 2004, 22 December 2004, 23 December 2004 and 12 January 2005), and 600 mm (23 December 2004) distance from willow trees (Figure 6.4). However, there were no significant effects at the other observation dates. For example on 23 December.2004 at 150 mm from willow trees, grazing and control treatments had higher SWC ($P < 0.0001$) than the herbicide treatment (34.5% = 33.8% > 31.6%, respectively). On 22 December 2004 at 300 mm from willow trees, the grazing treatment had higher SWC ($P < 0.03$) than the herbicide and control treatments, with means of 32.5% > 30.7% = 30.4%, respectively. A similar result was found at 600 mm from willow trees with the grazing treatment having higher SWC ($P< 0.02$) than the herbicide and control treatments (35.4% > 32.4% = 32.1%, respectively).

Overall, SWC was affected by pasture management treatments at 300 mm ($P < 0.0001$, LSD = 0.3) and 600 mm ($P < 0.0001$, LSD = 0.4) distances from willow trees, but not at 150 mm from willow trees. At 300 mm from willow trees, the grazing treatment had higher mean SWC than the control and herbicide treatments (24.1% > 23.5% > 22.8%, respectively). Grazing had higher SWC than the herbicide and control treatments at 600 mm from willow trees with means of 23.2% > 22.5% > 22.0%, respectively.

Figure 6.4 Effect of pasture management on volumetric soil water content at 0-450 mm soil depth.



6.3.5 Soil water loss/recharge per day

6.3.5.1 0 - 150 mm soil depth

Soil water loss per day was significantly affected by pasture management on 21-22 October 2004, 9-10 December 2004, 9-10 February 2005 and 23-24 February 2005 (Table 6.5.). For example on 21-22 October 2004, the control treatment had higher water loss per day than the grazing and herbicide treatments with means of -8.9 mm, -4.0 mm and -3.9 mm, respectively. On 9-10 December 2004 the grazing and control treatments had lower water loss per day than the herbicide treatment with means of -0.9 mm/day, -1.8 mm/day and -3.3 mm/day, respectively. However no significant effects were observed on the other observation dates (Table 6.5.).

Pasture management had no significant effect on overall mean soil water loss (Table 6.5).

There was a significant difference ($P < 0.05$) between soil water recharge per day for pasture management treatments on 22-23 December 2004 (Table 6.5). The control treatment had higher soil water recharge than the herbicide and grazing treatments with means of 16.1 mm/day > 11.1 mm/day = 10.4 mm/day, respectively (Table 6.5). No significant effects were observed on the other dates (25-26 November 2004, 10-11 March 2005 and 20-21 April 2005).

There was no significant difference between pasture management on overall mean of soil water recharge/day (Table 6.5).

Table 6.5 Effect of pasture management on soil water loss/recharge per day at 0-150 mm soil depth.

	Soil water loss /recharge (mm)					
	Pasture management				LSD	Probability
Date	Grazing	Herbicide	Control	Mean	(5 %)	
20-21.9.04	-5.9	-3.3	-7.9	-5.7	6.2	0.31
6-7.10.04	-5.5	-6.1	-5.5	-5.7	7	0.98
21-22.10.04	-4.0	-3.9	-8.9	-5.6	4.3	**0.01**
8-9.11.04	-4.0	-3.0	-3.4	-3.5	1.6	0.42
25-26.11.04	6.5	4.3	5.5	5.4	3.7	0.46
9-10.12.04	-0.9	-3.3	-1.8	-2.0	1.7	**0.03**
22-23.12.04	10.4	11.1	16.1	12.5	4.4	**0.03**
11-12.1.05	-3.3	-3.9	-2.4	-3.2	1.6	0.18
25-26.1.05	-1.8	-0.8	-1.3	-1.3	0.8	0.06
9-10.2.05	-2.1	-1.1	-0.8	-1.3	0.9	**0.03**
23-24.2.05	-1.7	-1.0	-0.7	-1.1	0.9	**0.05**
10-11.3.05	0.9	0.8	0.8	0.8	0.5	0.77
23-24.3.05	-1.1	-1.5	-0.8	-1.1	1.2	0.44
20-21.4.05	1.5	1.4	2.0	1.6	1.1	0.46
Overall mean SWL	-2.8	-2.9	-3.4	-3.0	1.1	0.52
Overall mean SWR	4.8	4.4	6.1	5.1	1.6	0.09

Note:
Negative value – soil water loss per day (SWL)
Positive value – soil water recharge per day (SWR)

6.3.5.2 0-300 mm soil depth

Pasture management had no significant effect on soil water loss per day during the experiment periods, except on 9-10 December 2004 (Table 6.6). The overall mean of soil water loss was not affected by pasture management (Table 6.6).

Soil water recharge was significantly affected by pasture management on 22-23 December 2004 (P = 0.01) (Table 6.6) with the control treatment having higher soil water recharge than the grazing and herbicide treatments with means of 16.5 mm/day > 12.1 mm/day > 5.5 mm/day, respectively. There were no significant effects at the other observation dates. The overall mean of soil water recharge was not affected by pasture management (Table 6.6).

Table 6.6 Effect of pasture management on soil water loss/recharge per day at 0-300 mm soil depth.

	Soil water loss /recharge (mm)					
	Pasture management				LSD	Probability
Date	Grazing	Herbicide	Control	Mean	(5 %)	
20-21.9.04	-9.4	-12.9	-13.8	-12.0	9.9	0.61
6-7.10.04	-5.3	-10.0	-10.0	-8.4	8.3	0.39
21-22.10.04	-11.0	-10.0	-8.0	-9.7	6.2	0.58
8-9.11.04	-5.1	-6.4	-5.6	-5.7	3.2	0.68
25-26.11.04	8.0	5.6	5.9	6.5	5.0	0.54
9-10.12.04	-3.1	-5.5	-3.5	-4.0	2	0.05
22-23.12.04	12.1	5.5	16.5	11.4	6.9	**0.01**
11-12.1.05	-6.9	-5.1	-5.8	-5.9	2.4	0.33
25-26.1.05	-2.0	-2.1	-1.8	-2.0	0.9	0.83
9-10.2.05	-1.2	-0.8	-1.0	-1.0	0.8	0.60
23-24.2.05	-1.6	-1.1	-1.5	-1.4	0.8	0.50
10-11.3.05	1.1	0.8	0.6	0.8	0.7	0.35
23-24.3.05	-1.3	-0.5	-1.4	-1.1	1	0.14
20-21.4.05	3.5	2.9	1.2	2.5	5.6	0.65
Overall mean SWL	-4.7	-5.4	-5.2	-5.1	1.3	0.51
Overall mean SWR	6.2	3.7	6	5.3	2.7	0.13

Note:
Negative value – soil water loss/day (SWL)
Positive value – soil water recharge/day (SWR)

6.3.5.3 0-450 mm soil depth

There were no significant differences between pasture management in soil water loss per day at 0-450 mm soil depth, except on 25-26 January 2005 (Table 6.7). Grazing and control treatments had higher soil water loss than the herbicide treatments with means of -2.7 mm/day = -2.6 mm/day > -1.7 mm/day, respectively. Overall soil water loss varied (P= 0.03) between treatments in the order control (-3.3 mm/day) > grazing (-2.6 mm/day) = herbicide (-2.2 mm/day) (Table 6.7).

There were no significant effects at pasture management on soil water recharge or overall mean of soil water recharge (Table 6.7).

Table 6.7 Effect of pasture management on soil water loss/recharge per day at 0-450 mm soil depth.

	Soil water loss /recharge (mm)					
	Pasture management				LSD	Probability
Date	Grazing	Herbicide	Control	Mean	(5 %)	
8-9.11.04	-3.5	-4.4	-5.1	-4.3	1.4	0.06
25-26.11.04	2.9	4.5	3.2	3.5	2.6	0.37
9-10.12.04	-3.1	-0.1	-4.9	-2.7	5.5	0.21
22-23.12.04	10.1	4.3	8.7	7.7	5.6	0.10
11-12.1.05	-7.5	-6.4	-5.0	-6.3	2.4	0.12
25-26.1.05	-2.7	-1.7	-2.6	-2.3	0.8	**0.03**
9-10.2.05	-2.1	-0.6	-1.1	-1.3	1.8	0.21
23-24.2.05	-0.9	-0.9	-1.1	-1.0	0.6	0.69
10-11.3.05	0.6	0.0	0.5	0.4	1.0	0.40
23-24.3.05	-0.6	-0.9	-0.9	-0.8	1.1	0.79
20-21.4.05	1.4	-0.1	0.7	0.7	2.6	0.48
Overall mean SWL	-2.6	-2.2	-3.3	-2.7	0.9	**0.03**
Overall mean SWR	3.8	2.2	3.3	3.1	1.8	0.21

Note:
Negative value – soil water loss (SWL)
Positive value – soil water recharge (SWR)

6.3.6 Water deficit from field capacity

6.3.6.1 0-150 mm planting depth

Soil water deficit was not significantly affected by pasture management from 20 September 2004 to 26 November 2004 (spring) (Table 6.8). Soil water deficit ranged from 0 mm to -30.1 mm for the control treatment, and 0 mm to -29.3 mm and -1.1 mm to -28.8 mm for the herbicide and grazing treatments, respectively.

Soil water deficit was significantly affected by pasture management on 23 December 2004, but not at any other time during summer/autumn (Table 6.8). On 23 December 2004 the herbicide treatment had higher soil water deficit (P=0.0001) than the grazing and control treatments (-6.3 mm, -2.4 mm and 0.0 mm, respectively). Pasture management had no significant effect on overall mean soil water deficit (Table 6.8).

Table 6.8 Effect of pasture management on soil water deficit from field capacity at 0-150 mm soil depth.

Date	Water deficit from field capacity (mm)			LSD (5%)	Probability
	Pasture management				
	Grazing	Herbicide	Control		
Spring					
20.9.04	-2.1	-0.2	-0.4	2.8	0.1386
21.9.04	-2.6	-2.1	-3.3	2.9	0.6920
6.10.04	-1.7	-1.0	-0.5	1.9	0.3892
7.10.04	-2.5	-1.4	-0.5	2.8	0.3366
21.10.04	-2.1	0.0	0.0	3.3	0.3255
22.10.04	-1.1	-0.2	-2.3	2.9	0.3372
8.11.04	-19.5	-20.1	-22.9	5.1	0.3254
9.11.04	-23.5	-23.1	-26.3	4.6	0.3036
25.11.04	-28.8	-29.3	-30.1	2.2	0.8414
26.11.04	-22.2	-25.0	-24.6	5.0	0.4549
Summer/Autumn					
9.12.04	-22.2	-21.3	-21.9	7.4	0.9677
10.12.04	-23.1	-24.6	-23.7	7.0	0.9001
22.12.04	-12.8	-17.4	-13.6	5.2	0.1693
23.12.04	-2.4	-6.3	0.0	2.2	**0.0001**
11.1.05	-12.2	-17.2	-14.3	5.0	0.1399
12.1.05	-15.5	-21.1	-16.7	5.1	0.0773
25.1.05	-34.3	-38.0	-36.1	4.3	0.2053
26.2.05	-36.0	-38.8	-37.4	4.0	0.3681
9.2.05	-43.8	-44.5	-44.5	3.5	0.8816
10.2.05	-45.9	-45.6	-45.9	4.0	0.9606
23.2.05	-45.5	-45.8	-45.5	4.9	0.9926
24.2.05	-47.3	-46.8	-46.2	5.1	0.9029
10.3.05	-45.9	-46.2	-46.0	5.0	0.9924
11.3.05	-45.0	-45.4	-45.2	4.9	0.9847
23.3.05	-45.4	-44.8	-44.7	4.1	0.9313
24.3.05	-92.9	-92.5	-91.0	9.5	0.9015
20.4.05	-87.0	-87.3	-89.5	6.7	0.6945
21.4.05	-84.0	-85.7	-85.5	2.2	0.8124
Overall mean SWD	-30.2	-31.0	-30.6	0.8	0.1305

6.3.6.2 0-300 mm planting depth

Soil water deficit was similar ($P > 0.05$) under the three pasture managements in spring 2004 (Table 6.9) and it ranged from 0 mm to -54.3 mm, 0 mm to -43.3 mm and 0 mm to -41.1 mm for the grazing, herbicide and control treatments, respectively.

Pasture management significantly affected soil water deficit on 23 December 2004, and 11 January 2005 and 12 January 2005 (Table 6.9). For example on 23 December 2004, the herbicide treatment had higher soil water deficit than

the grazing and control treatments (-21.7 mm > -7.8 mm = -4.0 mm, respectively). However there were no significant effects of pasture management on soil water deficit at the other observation dates in summer/autumn.

Averaged over all dates of measurement, pasture management significantly affected soil water deficit (Table 6.9) with the herbicide treatment (-43.4 mm) having a higher deficit than grazing (-39.9 mm) and control (-38.8 mm), which were not significantly different from each other.

Table 6.9 Effect of pasture management on soil water deficit from field capacity at 0-300 mm soil.

Date	Water deficit from field capacity (mm)			LSD (5%)	Probability
	Pasture management				
	Grazing	Herbicide	Control		
Spring					
20.9.04	-0.1	-1.6	0.0	2.8	0.402
21.9.04	-0.2	-4.3	-1.2	4.1	0.1128
6.10.04	0.0	0.0	0.0	0 0	0.1000
7.10.04	0.0	-0.7	-1.1	1.3	0.2083
21.10.04	-0.2	0.0	0.0	0.4	0.3945
22.10.04	-0.4	-0.5	-0.7	1.3	0.8817
8.11.04	-24.2	-23.6	-24.7	5.7	0.3116
9.11.04	-29.3	-30.0	-30.3	4.6	0.8808
25.11.04	-54.3	-43.3	-41.8	6.8	0.5400
26.11.04	-37.3	-37.7	-35.9	7.2	0.8444
Summer/Autumn					
9.12.04	-26.8	-31.1	-27.0	8.1	0.4519
10.12.04	-29.8	-36.5	-30.4	7.8	0.1621
22.12.04	-19.9	-27.2	-20.4	8.1	0 1344
23.12.04	-7.8	-21.7	-4.0	6.5	**0.0001**
11.1.05	-15.5	-25.8	-15.2	7.6	**0.0155**
12.1.05	-22.4	-30.9	-21.0	8.1	**0.0408**
25.1.05	-57.4	-64.1	-57.2	6.6	0.0678
26.2.05	-59.4	-66.2	-59.0	6 7	0.0670
9.2.05	-73.2	-75.6	-70.6	7.1	0.3466
10.2.05	-74.4	-76.3	-71.5	7.2	0.3822
23.2.05	-74.2	-76.9	-72.2	8.0	0.4552
24.2.05	-75.7	-78.0	-73.6	7.9	0.4995
10.3.05	-76.2	-79.2	-73.6	7.9	0.3403
11.3.05	-73.1	-75.1	-78.5	7.6	0.3291
23.3.05	-76.3	-78.9	-72.7	8.4	0.3157
24.3.05	-77.6	-79.4	-74.1	8.5	0.4160
20.4.05	-71.9	-75.4	-69.3	8.7	0.3457
21.4.05	-68.4	-72.5	-68.2	7.5	0.4007
Overall mean SWD	-40.0	-43.4	-38.8	1.2	**0.0001**

6.3.6.3 0-450 mm planting depth

Soil water deficit was not affected by pasture management at any measurement date in spring 2004 (Table 6.10). Pasture management significantly affected soil water deficit from 10 December 2004 to 12 January 2005 (Table 6.10). For example on 23 December 2004, the herbicide treatment had higher soil water deficit (-22.7 mm) than the control (-18.5 mm) and grazing (-11.8 mm) treatments. There were no significant differences in soil water deficit for the pasture management treatments at the other observation dates in summer/autumn (Table 6.10).

Across spring, summer and autumn, pasture management significantly affected soil water deficit in the order herbicide treatment (-48.6 mm) > control treatment (-46.4 mm) > grazing treatment (-44.7 mm) (Table 6.10). The water required to reach field capacity in all treatments ranged from 11.8 mm to 40.2 mm from 8 November 2004 to 12 January 2005. From 25 January 2005 to 21 April 2005, more water was required, ranging from 50.3 mm to 68.2 mm (Table 6.10).

Table 6.10 Effect of pasture management on soil water deficit from field capacity at 0-450 mm soil depth.

Date	Water deficit from field capacity (mm)			LSD 5%	Probability
	Pasture management				
	Grazing	Herbicide	Control		
Spring					
8.11.04	-20.7	-24.1	-20.9	4.1	0.1694
9.11.04	-23.3	-27.4	-24.8	4.4	0.1686
25.11.04	-35.5	-40.2	-36.5	4.4	0.0870
26.11.04	-33.3	-36.8	-34.1	4.3	0.2323
Summer/Autumn					
9.12.04	-27.0	-31.9	-28.7	4.3	0.0790
10.12.04	-29.3	-34.7	-31.8	3.8	**0.0312**
22.12.04	-19.4	-26.0	-25.1	5.0	**0.0303**
23.12.04	-11.8	-22.7	-18.5	2.6	**0.0001**
11.1.05	-17.3	-22.9	-15.9	4.0	**0.0057**
12.1.05	-21.1	-27.7	-21.6	3.6	**0.0022**
25.1.05	-50.3	-55.4	-51.7	4.8	0.0990
26.2.05	-52.3	-56.7	-53.6	4.9	0.1749
9.2.05	-61.6	-64.5	-63.2	2.2	0.6613
10.2.05	-63.2	-64.9	-64.1	6.3	0.8353
23.2.05	-64.6	-66.3	-66.6	5.2	0.6768
24.2.05	-65.3	-67.0	-67.4	5.4	0.6656
10.3.05	-65.7	-67.6	-67.3	5.6	0.7480
11.3.05	-65.3	-67.6	-66.9	5.6	0.6708
23.3.05	-66.1	-67.5	-67.5	5.4	0.8082
24.3.05	-66.5	-68.2	-68.2	5.5	0.7590
20.4.05	-63.3	-65.1	-63.7	4.7	0.7004
21.4.05	-62.2	-65.1	-63.2	5.1	0.4701
Overall mean SWD	-44.7	-48.6	-46.4	1.0	0.0001

6.3.7 Stem water potential

Pasture management significantly affected ($P < 0.001$) stem water potential on 21 October 2004, 8 November 2004 and 25 November 2004 (Table 6.11). For example on 8 November 2004 the control and herbicide treatments had higher stem water potential than the grazing treatment (- 0.80 MPa = - 0.79 MPa > - 0.67 MPa, respectively). However, no significant differences were observed on 20 September 2004 and 6 October 2004 (Table 6.11). The control treatment (- 0.65 MPa) had higher mean stem water potential than the grazing treatment (- 0.59 MPa), but it was similar to the herbicide (-0.63 MPa) treatment (Table 6.11).

Stem water potential was affected ($P < 0.05$) by pasture management at all measurement dates in summer/autumn, except on 11 January 2005 (Table

6.12). Higher water stress was observed from 25 January 2005 to 24 March 2005. For example, on 9 February 2005 the control and herbicide treatments had higher water stress than the grazing treatment with mean stem water potential of -1.86 MPa, -1.75 MPa and -1.57 MPa, respectively. A similar result was also found on 24 March 2005 (Table 6.12). Overall the control treatment (-1.48 MPa) had higher mean stem water potential than the grazing treatment (-1.28 MPa), but it was similar to the herbicide (-1.37 MPa) treatment (Table 6.12).

Table 6.11 Effect of understorey pasture management on willow stem water potential in spring, 2004.

Treatment	Stem water potential (MPa)				
	Date				
	20.9.04	6.10.04	21.10.04	8.11.04	25.11.04
Grazing	-0.59	-0.56	-0.45	-0.67	-0.67
Herbicide	-0.61	-0.57	-0.40	-0.79	-0.79
Control	-0.62	-0.58	-0.48	-0.80	-0.81
LSD	0.05	0.04	0.04	0.07	0.07
Probability	ns	ns	0.002	0.0008	0.0006

Table 6.12 Effect of understorey pasture management willow on stem water potential in summer/Autumn 2004/2005.

Treatment	Stem water potential (MPa)						
	Date						
	9.12.04	22.12.04	11.1.05	25.1.05	9.2.05	24.2.05	24.3.05
Grazing	-0.75	-0.65	-0.74	-1.31	-1.57	-1.52	-1.88
Herbicide	-0.80	-0.64	-0.83	-1.5	-1.75	-1.56	-1.96
Control	-0.97	-0.8	-0.79	-1.44	-1.86	-1.76	-2.08
LSD	0.10	0.08	0.10	0.13	0.15	0.11	0.15
Probability	0.0002	0.0007	ns	0.0201	0.0016	0.0003	0.0253

6.3.8 Relationship between soil water content and stem water potential, and stem water potential and soil water deficit to predict water requirements of willow

6.3.8.1 300 mm distance from tree at 0-150 mm soil depth

There was a highly significant positive relationship (R^2=0.83) between stem water potential of willow and soil water content in all treatments, 300 mm from trees at 0-150 mm soil depth (Figure 6.5). There was also a significant positive relationship (R^2= 0.81) between stem water potential and soil water deficit from field capacity (Figure, 6.6). The fitted functions were used to provide the predicted values of water requirement for irrigation up to 150 mm soil depth (Table 6.13).

Figure 6.5 Relationship between soil water content (300 mm distance from trees at 0-150 mm soil depth) and stem water potential of willow in a willow-pasture agroforestry system (n= 107 , p < 0.0001).

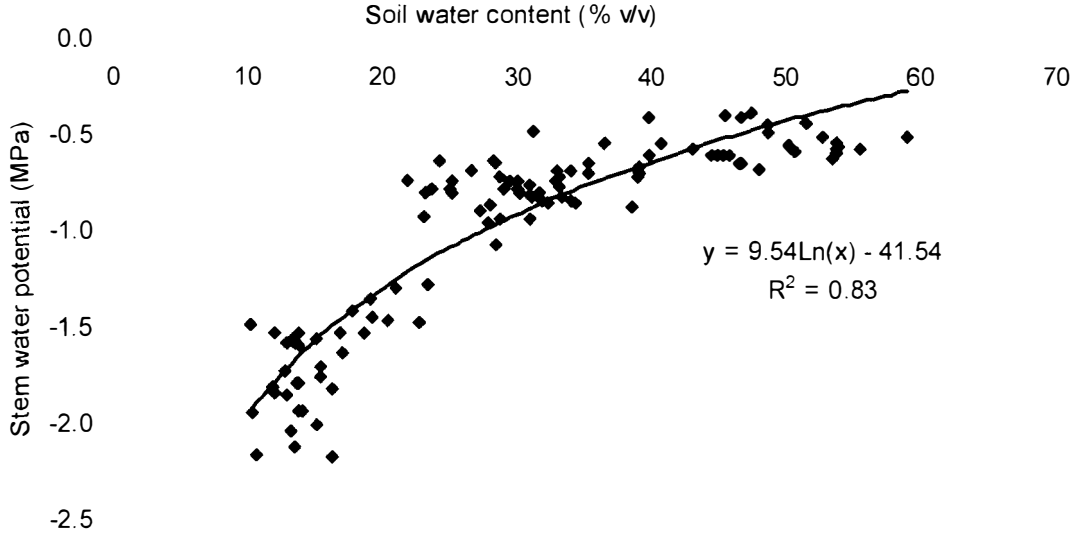


Figure 6.6 Relationship between stem water potential and soil water deficit from field capacity (300 mm distance from trees at 0-150 mm soil depth) in a willow-pasture agroforestry system (n=107, $p < 0.0001$).

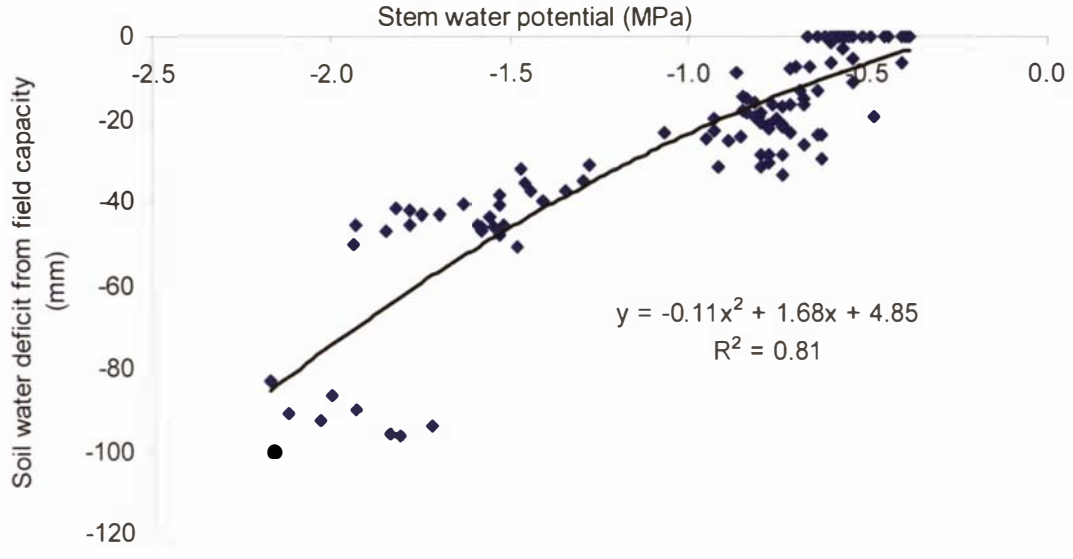


Table 6.13 Predicted water requirement to reach field capacity, using either soil water content (300 mm from willow trees at 0-150 mm soil depth) or stem water potential.

Soil water content (% v/v)	Stem water potential (MPa)	Water required to field capacity (mm)
42	-0.59	7.9
40	-0.63	9.9
35	-0.76	15.6
30	-0.91	22.1
25	-1.08	29.7
20	-1.30	39.2
15	-1.57	51.4
10	-1.96	68.5

6.3.8.2 300 mm distance from tree at 0-300 mm soil depth

There was a highly significant positive relationship between stem water potential (R^2 =0.87)(Figure 6.7) and soil water content in all treatment, 300 mm from trees at 0-300 mm soil depth. There was also a significant positive relationship (R^2 = 0.87) between stem water potential and soil water deficit from

field capacity (Figure 6.8). The fitted functions were used to provide the predicted values of water requirement for irrigation up to 0-300 mm soil depth (Table 6.14).

Figure 6.7 Relationship between soil water content (300 mm distance from trees at 0-300 mm soil depth) and stem water potential of willow in a willow-pasture agroforestry system (n= 107 , p < 0.0001).

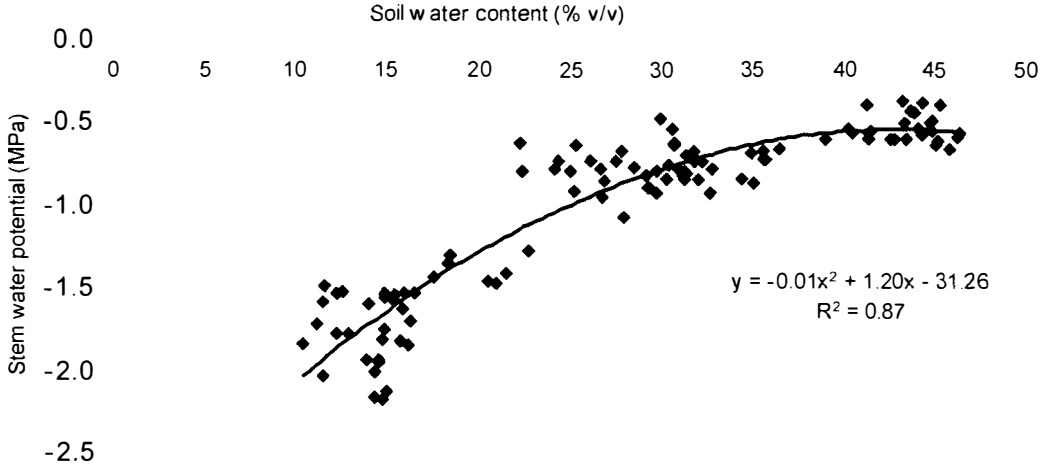


Figure 6.8 Relationship between stem water potential and soil water deficit to field capacity (300 mm distance from trees at 0-300 mm soil depth) in a willow-pasture agroforestry system (n=107, p < 0.0001).

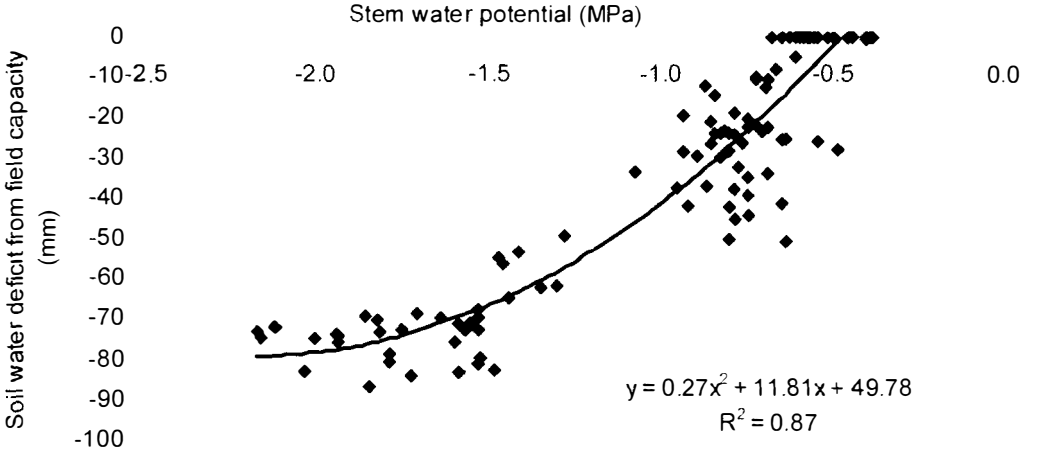


Table 6.14 Predicted water requirement to reach field capacity, using either soil water content (300 mm from willow trees at 0-300 mm soil depth) or stem water potential.

Soil water content (% v/v)	Stem water potential (MPa)	Water required to field capacity (mm)
40	-0.01	0.0
35	-0.15	0.0
30	-0.43	4.3
25	-0.75	21.4
20	-1.13	41.0
15	-1.55	63.2
10	-2.03	88.1

6.3.8.3 300 mm distance from tree at 0-450 mm soil depth

There was a highly significant positive relationship between stem water potential (R^2 = 0.87) (Figure 6.9) and soil water content in all treatments, 300 mm from trees at 0-450 mm soil depth. There was also a significant positive relationship between stem water potential and soil water deficit from field capacity (R^2 = 0.86) (Figure 6.10). The fitted functions were used to provide the predicted values of water required for irrigation up to 0-450 mm soil depth (Table 6.15).

Figure 6.9 Relationship between soil water content (300 mm distance from trees at 0-450 mm soil depth) and stem water potential of willow in a willow-pasture agroforestry system (n= 107 , p < 0.0001).

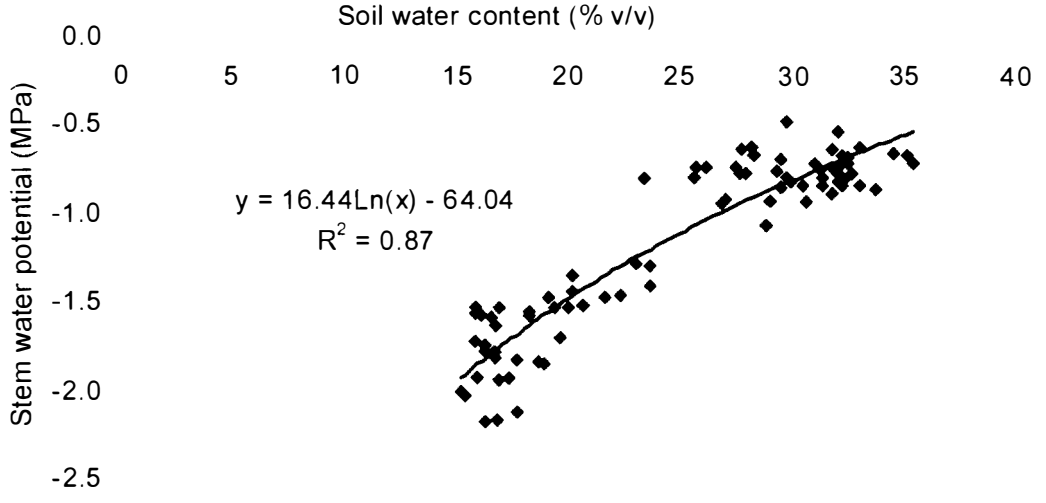


Figure 6.10 Relationship between stem water potential and soil water deficit to field capacity (300 mm distance from trees at 0-450 mm soil depth) in a willow-pasture agroforestry system (n=107, $p < 0.0001$).

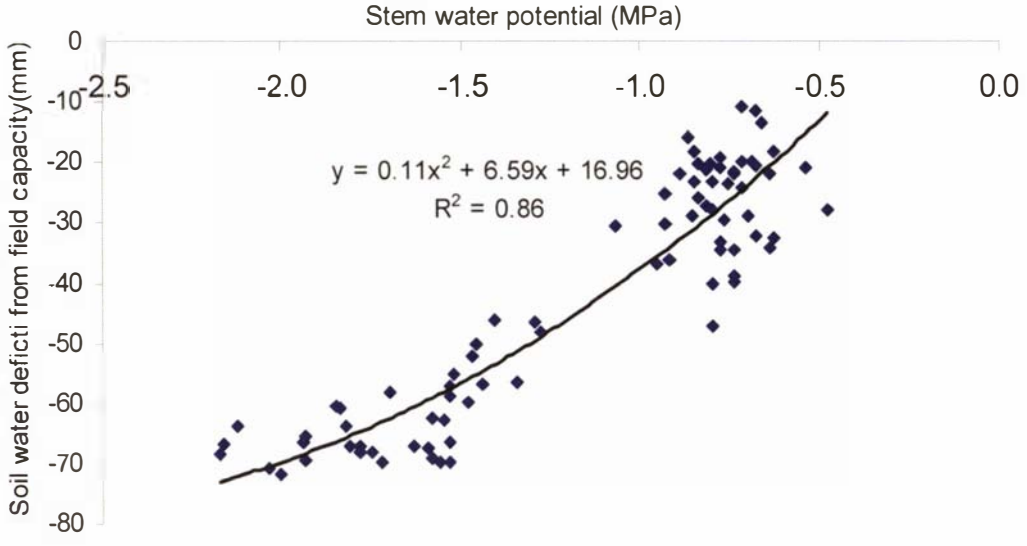


Table 6.15 Predicted water requirement to reach field capacity, using either soil water content (300 mm from willow trees at 0-450 mm soil depth) or stem water potential.

Soil water content (% v/v)	Stem water potential (MPa)	Water required to field capacity
38	-4.2	-8.8
35	-5.6	-16.2
30	-8.1	-29.1
25	-11.1	-42.6
20	-14.8	-56.3
15	-19.5	-69.7
10	-26.1	-80.1

6.4 Discussion

6.4.1 Treatment effects on soil water content

Pasture management had a significant effect on overall mean soil water content (SWC) at all depths, except 150 mm from willow trees at 0-300 mm and 0-450 mm soil depths, but the difference was too small to have an impact on soil water conservation particularly during the drought season. When analysis was conducted for each date of measurement, the results indicated that pasture management often had no impact on SWC with significant differences only observed on certain dates particularly when SWC was measured in early and mid summer. Barker *et al*. (1985) also found no significant effect of defoliation treatments of perennial ryegrass on SWC. The absence of an effect of pasture management on SWC may be because of: (i) adequate water during spring (ii) dryness during summer/autumn caused little or no soil water uptake by trees for transpiration, and (iii) similar total root density was found beneath pasture management treatments at different soil depth and distance (Tables 6.2, 6.3 and 6.4).

Grazing and/or control treatments had higher SWC than the herbicide treatment particularly during December 2004 and January 2005 at 150 mm and 300 mm from willow trees at 0-150 mm, 0-300 mm and 0-450 mm soil depths. This may be because during moderately moist conditions, understorey pasture cover caused lower evaporation, and thus, soil water was conserved. This was supported by Brougham (Brougham 1959, 1960) who found actively growing pastures with herbage cover had up to 25% higher SWC than heavily grazed pasture. A significant effect of pasture management on SWC was only found 600 mm from willow trees at 0-450 mm soil depth. It was unclear why higher SWC was found for grazing and control treatments at 0-450 mm soil depth because less competition for soil water was expected between pasture roots at deeper soil depths. A previous study also found that 90% of pasture root density occurred at 300 mm soil depth (Eastham *et al*. 1990) with greatest root density in the first 200 mm soil depth (Rodrigues & Cadima-Zevallos 1991). It is

possible that the high SWC in the grazing and control treatments was because the pasture covers influenced evapotranspiration and water run-off.

The results found that the pasture management treatments had no significant effect on SWC particularly in spring (September to November 2004) and summer/autumn (February to April 2005). Growth of willows was not affected in any treatment in spring due to favourable weather conditions. In summer (December 2004 and January 2005), pasture management often had a significant effect on SWC. Grazing and control treatments conserved higher SWC during this period. Higher SWC in the grazing treatment may cause higher willow growth compared to the control treatment where competition for water and nutrient is foremost. Previous research (Chapter 3) also found higher survival and growth of willows with understorey defoliation (mowing). Low SWC particularly during February to early April 2005 was the critical period for young willow trees (3 years old). Visual observation found leaves and tips of the shoots dying during this period in all treatments, but the adverse effect was not sufficient to cause death of willow trees. However, if water shortage occurs for young willow during early establishment, the potential mortality could be increased. Therefore, for good establishment of young trees, early planting needs to be considered for initiation of roots before the start of the dry season. Results presented here are based on one year experiments, and to confirm the findings, the experiment would need to be repeated at least three years before final conclusions can be made.

6.4.2 Effect of pasture management treatments on soil water deficit to field capacity

Pasture management had an impact on overall mean soil water deficit at 0-300 mm and 0-450 mm soil depths. However, the effects were only observed on certain dates, three dates out of 28 measurement dates (23 December 2004 and 11 and 12 December 2005) at 0-300 mm soil depth, and four dates (10, 22, 23 December 2004 and 12 January 2005) at 0-450 mm depth, which influenced overall results. Pasture management had a positive impact on soil water deficit particularly during early or mid summer. Herbicide treatment with

negligible or no pasture cover had the highest water deficit, whereas similar water deficits were observed from grazing and control treatments during the period. Lower soil water deficit, or higher SWC, from control and grazing treatments, may be because of less water run-off due to better infiltration through the pasture cover and root system especially during soil water recharge. This was supported by Tennant *et al.* (2001) who found rates of soil drying can be influenced by ground cover and transpiration. Development of more macropores (Rachman *et al.* 2004a; Rachman *et al.* 2004b), pore continuity (Rasse *et al.* 2000; Cadisch *et al.* 2004), formation of soil aggregates (Wienhold & Tanaka 2000) and decayed roots from agroforestry (willow and pasture), may have increased soil water storage. During spring or late summer, pasture management had no effect on soil water deficit. All treatments conserved similar amounts of water during higher rainfall in spring and had higher water deficits in late summer/autumn.

6.4.3 Effect of pasture management treatments on soil water loss/recharge

Overall mean soil water loss/recharge per day was not affected by pasture management except at 0-450 mm soil depths. Control and grazing treatments had higher mean soil water losses than the herbicide treatment at 0-450 mm soil depth. It was not clear why control and grazing treatments had higher soil water losses as there was probably no competition between pasture and willow at deeper soil depths (0-450 mm). A possible reason is that greater competition between roots of pasture and willow occurred at 0-300 mm depth which caused willow roots to abstract more water from deeper soil (0-450 mm). Significant effect of pasture management on soil water loss observed on certain dates, however, responses depended on soil depth. Only four dates (21-22 October 2004, 9-10 December 2004, 9-10 February 2005 and 23-24 February 2005) out of 10 measurement dates were found to have significant effects of treatments on soil water loss per day at 0-150 mm soil depth (Table, 6.5) compared with one date at the 0-300 mm (9-10 December 2004) (Table 6.6) and 0-450 mm (26 January 2005) (Table 6.7) soil depths. This indicated that the soil depth of 0-150 mm was more sensitive to pasture management than depths of 0-300 and

0-450 mm. This was possibly because: (i) understorey pasture cover influenced soil water loss and (ii) higher total root density of pasture at 0-150 mm than other depths caused more water use. Rodrigues *et al.* (1991) also found the highest % of pasture roots at 0-200 mm soil depth.

Higher soil water loss per day was found in spring when mean soil water loss ranged from -3.5 mm to -5.7 mm, -5.7 mm to -12 mm and -4.3 mm per day for 0-150 mm, 0-300 mm and 0-450 mm soil depths, respectively (Tables 6.6, 6.7 and 6.8). The higher soil water loss from the 0-300 mm depth may have been because of the higher total root density of willow at that depth. The maximum water loss per day occurred on 20-21 September 2004 at the 0-300 mm depth was -12 mm/day. This high water loss was because of non-limiting water supply during time of measurement resulting in higher water use by transpiration and water loss through drainage. A similar result was found by Hall *et al.* (1998) with *Salix burjatica* with peak water loss by evapotranspiration of -11 mm/day. As water stress increased in summer/autumn the mean soil water loss decreased ranging from -1.1 to -3.2 mm per day, -1.0 to -5.9 mm per day and -0.8 to -6.3 mm per day for 0-150 mm, 0-300 m and 0-450 mm soil depths, respectively. The reduced water loss may have been because of a lack of water to transpire.

6.4.4 Effect of pasture management on stem water potential and prediction of water requirement of willow

The control and herbicide treatments always had higher negative stem water potential than the grazing treatment from 21 October 2005 to 11 January 2005, except on 21 October 2004, where the grazing and control treatments had higher negative stem water potential than the herbicide treatment. The similar stem water potential on 21 October 2004 between grazing and control treatments were most likely because the grazing treatment was not imposed until 6 November 2004. The higher negative stem water potential of control and herbicide treatments during non-stressed conditions in spring and early summer was probably due to higher water use by willow and pasture in the control treatment, in contrast in the herbicide treatment, higher water losses were

attributed to higher evopotranspiration due to negligible pasture cover. Similarly, Vidhana Arachchi *et al.* (2003) found higher soil water loss for trees growing in bare soil than in an agroforestry system.

During high water stress in summer from 25 January 2005 to 24 March 2005, the control and herbicide treatments showed a similar trend, with higher negative stem water potential than the grazing treatment. The result for the control and herbicide treatments might be because of higher competition for soil water between willow and pasture in the control treatment, and higher evapotranspiration, and low SWC in the herbicide treatment. From visual observation, willow at -1.5 MPa and more had severe leaf drop and shoots dying. A similar symptom was found on Yellow poplar (*Liriodendron tulipifera*) during higher water stress (Chaney 2000). Water stress in prune tree (-1.5 MPa or more) can cause fruit cracking and drop (Shackel 2004). Leaf drop and shoot death during water stress causes reduced photosynthesis and carbohydrate storage, which can affect growth and biomass production after the drought conditions (Chaney 2000). This was relevant to the slow growth of willow established in 2002 (Chapter 3) which suffered severe drought during establishment, compared to the willows established in 2003 (Chapter 4) which grew under favourable weather conditions and produced higher shoot biomass.

A strong relationship was found between SWC (%) and stem water potential. As SWC increased, stem water potential decreased. The relationship between stem water potential and soil water deficit was used to predict the amount of water required for irrigation to field capacity by measuring either SWC (%) or stem water potential. This can help farmers to detect water stress before it has a serious effect on willow growth and biomass production. High water deficits were observed from 25 January 2005 to 21 April 2005. Stem water potential during this date ranged from -1.3 MPa to -1.5 MPa. At this water potential, leaves started to change colour and ultimately abscised from wilting. Therefore water supply is needed before this stage to ensure shoot growth is not affected by water stress.

The grazing treatment was significantly better for managing the willow pasture system particularly under low water conditions (during drought). Grazing will

reduce potential understorey leaf area that influences evapotranspiration. Therefore for those farmers interested in establishing willow pasture blocks, it is better for them to allow grazing to minimise water stress.

6.5 Conclusion

During seven months of study between 20 September 2004 to 21 April 2005, the mean soil water content (SWC) was varied significantly between pasture management treatments at 0-150 mm, 0-300 mm and 0-450 mm soil depths at all distances (150 mm, 300 mm and 600 mm) from willow trees, except 150 mm from willow trees at 0-300 mm and 0-450 mm soil depths. The grazing or control (no weed control) treatments had higher mean SWC than the herbicide treatment. However, no significant difference in SWC was found, particularly during spring 2004 and late summer/autumn 2005. During wet periods in spring and a dry period in late summer/autumn, SWC was similar between the pasture management treatments.

Pasture management had no effect on overall mean soil water loss per day at 0 -150 mm (- 0.7 mm per day to - 8.9 mm per day) and 0-300 mm (-0.5 mm per day to - 13.8 mm per day) soil depths. However, a significant difference in mean soil water loss occurred at 0-450 mm soil depth, with the control treatment having higher soil water loss than the herbicide treatment (-3.3 mm/day vs -2.2 mm/day, respectively), but similar to the grazing treatment (-2.6 mm/day). This may have been because higher competition between pasture and willow roots caused willow roots at 450 mm soil depth to use more water in the grazing and control treatments.

Overall mean water deficit from field capacity was affected by pasture management at 0-300 mm and 0-450 mm soil depths. Higher water deficit in the herbicide treatment compared to the grazing or control treatments, might have been because negligible pasture cover increased water losses through evapotranspiration and greater run-off.

The control and herbicide treatments had higher mean stem water potential than the grazing treatment. This suggested that higher water stress occurred in

the control and herbicide treatments than the grazing treatment, indicating higher competition occurred between roots of willow and pasture in the control treatment, while water losses through evaporation caused higher stress from herbicide treatment.

The strong relationships between (i) SWC and stem water potential and (ii) stem water potential and soil water deficit, can help growers to predict the amount of water required during growing season of willows.

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7 Effect of sheep grazing on newly planted willow and poplar.

CONTENT

7.1 Introduction

Trees and shrubs can provide supplementary fodder during summer drought when pasture production is reduced and pastures are of poor quality. Feeding tree fodder to farm animals is commonly practised in New Zealand, as summer droughts are too harsh for pastures to grow well and this affects sheep production (McWilliam e*t al.* 2003). Farmer experience has shown that using willow and poplar trees originally planted for soil conservation purposes, as a source of fodder for livestock, is one approach to overcoming summer feed shortages (McWilliam e*t al*. 2003; Olsen & Charlton 2003).

The leaves and twigs (< 5 mm diameter) of willow are often used in dry summers as supplementary forage (Kemp e*t al*. 2001). As the nutritive value of willow and poplar is similar to normal summer pasture and better than summer drought pasture (McCabe & Barry 1988; Kemp e*t al*. 2001)it is a useful source for animal food in summer. Although willow and poplar are potentially a major forage resource on many hill farms in New Zealand, there is lack of information available on the effect of grazing on survival and growth of willow and poplar trees.

Willow and poplar fodder can be supplied to animals on farms by cut and carry or direct browsing. A negative impact of animal grazing on trees has been reported by Ringe e*t al*. (1984), who found reduced survival and growth of seedling virginia pine (*Pinus virginiana*). However, a contrasting result was observed by Cutter e*t al*. (1999) who found no effect of grazing on tree height, tree diameter and growth of slash pine (*Pinus elliottii*). Preliminary experiments were focused on agronomic aspects: (i) establishment and (ii) understorey pasture management effects on biomass and soil water, but little information is available on the effect of sheep damage on various stem cuttings during establishment of willow and poplar. The objectives of this trial were (i) to determine the effect of sheep grazing on willow and poplar established from stem cuttings of three diameters on shoot intake and regrowth biomass of willow and poplar, and (ii) to determine the effect of grazing on tree survival and severity of tree damage.

7.2 Material and methods

7.2.1 Experimental site

The trial was located at the Pasture and Crop Unit, Moginie, Massey University, Palmerston North (longitude 175 ^{o} 37' E, latitude 40 ^{o} 21' S, altitude 30 m above sea level), on a Tokomaru silt loam with aeric fragiaqualf (gleyed yellow-grey earth) from February 2005 to May 2005. Rainfall and temperature during the growing season were obtained from AgResearch Grasslands, Palmerston North, 2.5 km from the experimental site. Rainfall during February, March and April 2005 was 25 mm, 41 mm and 52 mm, respectively. Maximum/minimum temperatures were 25.2/15.4 ^{o}C, 22.3/11.9 ^{o}C and 18.3/6.9 ^{o}C for February, March and April, respectively.

Willow and poplar trees were selected from a previous trial (Experiment 2 - Chapter 4) which was established on 6 August 2003 (18 months after planting).

7.2.2 Experimental treatments and design

Factorial treatments were arranged in three randomized complete blocks and each experiment unit was 5 m x 5 m with 36 plants per plot, with a total of 18 plots (3 stem diameters x 2 species x 3 replicates). All the trees were cut using loppers on 7 February 2005 at 1.3 m height to suit browsing by sheep (Oppong 1998). Sheep grazing was conducted from 10 February to 13 February 2005, with 108 sheep allowed to graze in all plots during the experiment period.

The treatments were:

i. Stem diameter: The three stem diameters during planting were: (i) 10 mm (range 9-12 mm); (ii) 25 mm (20-30 mm); and iii) 35 mm (31-40 mm). Both willow and poplar were established from 600 mm long stem cuttings planted at 300 mm depth.

ii. Plant species: The species were (i) *Salix matsudana* Koidz *x alba* L (willow; clone 'Tangoio') and ii) *Populus deltoides x nigra* (poplar; clone 'Veronese').

7.2.3 Tree measurements

7.2.3.1 Percentage of tree mortality

Tree mortality was surveyed on 1 May 2005 to determine the effects of sheep grazing on willow and poplar survival. All the tree mortality data were calculated in terms of percentage.

7.2.3.2 Percentage of tree damage

After the sheep were grazing from 10 February 2005 to 13 February 2005 a number of trees were found damaged to different degrees. The percentage of tree damage including main stems broken, branches broken, and trees leaning were surveyed on 1 March 2005. Tree leaning was determined as those trees which were not vertical and moveable by hand pushing.

7.2.3.3 Biomass of trees and pasture

Biomass of pasture and trees in all treatments was determined. All edible (leaf and stem < 5 mm diameter) willow and poplar material was harvested pre- and post-grazing. A total of 18 trees pre-harvest or 9 trees from willow and 9 trees from poplar (1 tree/plot) were harvested using different trees each time, during pre- and post-grazing. Pasture herbage, pre- and post-grazing was sampled to ground level, three quadrates (0.1 m^2) per treatment. All tree and herbage samples were oven dried for 24 to 48 hours. Mean biomass of tree and pasture components in each treatment was calculated as kg DM/ha. Parameters estimated included (i) Net utilisation of tree or pasture = biomass pre-graze - biomass post-graze, (ii) Percentage (%) of tree utilisation = (biomass pre-graze - biomass post-graze)/(pre-graze) * 100, (iii) % of tree eaten from agroforestry (% TEA) = (quantity of tree eaten)/(quantity of tree + pasture eaten) * 100.

7.2.3.4 Biomass regrowth of tree and pasture after grazing

Willow and poplar trees and pasture were allowed to regrow after grazing for 79 days from 13 February 2005 to 4 May 2005. Biomass regrowth of trees or pasture = biomass 79 days after grazing – biomass immediately after grazing.

7.2.4 Statistical analysis.

All data were analysed by Analysis of Variance (ANOVA), with the General Linear Model (GLM) procedure of the Statistical Analysis System (SAS 2001). The Least Significant Difference test at the 5% significance level was used to separate means.

7.3 Results

7.3.1 Effect of sheep grazing and stem cuttings diameter on tree damage.

There were no significant effects of stem diameter, species or their interaction on main stems broken, branches broken and tree leaning (Table 7.1). The means for tree damage were 1.5%, 0.5% and 2 % for main stems broken, branches broken and tree leaning, respectively (Table 7.1, also see Photo 7.1).

Table 7.1 Effect of grazing and stem size on tree damage.

		Tree Damage (%)		
Stem diameter (mm)	Species	Main stem broken %	Branch broken %	Tree leaning %
10	Willow	2	0	0
25	Willow	0	1	3
35	Willow	0	0	2
10	Poplar	5	1	0
25	Poplar	2	1	7
35	Poplar	0	0	0
SEM (D*S)		1.5	0.7	2.8
Variable:			Probability	
Species (S)		0.23	0.58	0.37
Stem diameter (D)		0.23	0.40	0.24
D*S		0.66	0.72	0.70

a) Main stem broken of poplar.

b) Branch broken of willow.

Photo 7. 1 Effect of grazing of willow and poplar on tree damage.

7.3.2 Effect of sheep grazing on tree mortality

Sheep grazing had no effect on willow and poplar mortality (Table 7.2). There were no significant differences between stem diameter and interaction of species and stem diameter on tree mortality (Table 7.2).

Table 7.2 Effect of sheep grazing and stem diameter on mortality of trees 18 months after field planting.

Stem diameter (mm)	Species	Tree death (%)
10	Willow	2
25	Willow	1
35	Willow	0
10	Poplar	4
25	Poplar	2
35	Poplar	0
SEM (D*S)		1.6
Variable:		Probability
Stem diameter (D)		0.37
Species (S)		0.10
D*S		0.78

7.3.3 Sheep utilisation of willow and poplar with different stem diameters.

The biomass of trees in all treatments before grazing was less than 800 kg DM/ha and ranged from 647 to 767 kg DM/ha for willow and 510 to 790 kg DM/ha for poplar (Table 7.3).

Grazing by sheep resulted in a net utilisation of willow edible biomass of 537, 221, and 332 kg DM/ha for 10 mm, 25 mm and 35 mm stem diameters, respectively. Willow stems of 10 mm diameter had higher % utilisation (70%) compared to those from 35 and 25 mm (41 and 34%, respectively). Net utilisation of poplar established from 10 mm, 25 mm and 35 mm diameter stems was 510, 287 and 544 kg DM/ha of edible biomass, respectively. Higher utilisation of poplar was found for 35 mm stem diameter (78%) than 10 mm (55%) and 25 mm (47%).

Pre-graze pasture mass ranged from 2546 kg DM/ha to 5293 kg DM/ha under willow and 4410 to 5576 kg DM/ha under poplar. After grazing by sheep, net utilisation of pasture was 457 to 2153 kg DM under willow and 1316 to 2363 kg DM under poplar (Table 7.3).

The percentage of willow eaten by sheep from the agroforestry system (%TEA) ranged from 21 to 46%, with the highest percentage was for stem diameter 35 mm (46 %) (Table 7.3). The highest % of poplar eaten in the agroforestry system was from stem diameter 35 mm, followed by 25 mm and 10 mm (34% > 24% > 18%, respectively).

Table 7.3 Pre- and post- grazing edible biomass (kg DM/ha) of willow and poplar at Massey University (Moginie) grazed in all treatments with 108 sheep in autumn 2003 (sample number per treatment = 3; standard deviation in bracket).

Species	Stem diameter (mm)	Edible Biomass (kg DM/ha)							% TEA
		Pre-graze		Post-graze		Pasture	Tree		
		Pasture	Tree	Pasture	Tree	Net utilisation	Net utilisation	% utilisation	
Willow	10	5293	767	3140	230	2153	537	70	21
		(1141)	(673)	(1630)	(106)	(876)	(487)		
	25	4723	647	3523	426	1200	221	34	19
		(1268)	(184))	(650)	(210)	(805)	(147)		
	35	2546	745	2090	412	457	332	41	46
		(709)	(180)	(741)	(81)	(377)	(253)		
Poplar	10	5310	790	3596	281	1713	510	55	18
		(1329)	(432)	(2204)	(154)	(875)	(480)		
	25	5576	510	3213	223	2363	287	47	24
		(1557)	(262)	(973)	(41)	(1778)	(239)		
	35	4410	713	3093	169	1316	544	78	34
		(386)	(231)	(1028)	(128)	(794)	(147)		

% TEA (% of tree eaten from agroforestry) = (quantity of tree eaten)/ (quantity tree + pasture eaten) * 100

7.3.4 Effect of sheep grazing on regrowth of edible biomass

There was no significant interaction between species and stem diameter on regrowth of tree edible biomass, pasture and total biomass (tree and pasture) (Table 7.4).

Trees established from thick stems (35 mm) had higher ($P < 0.0002$) regrowth of edible biomass than those established from 25 mm and 10 mm diameter stem cuttings with means of 7 > 3 = 1 kg DM/ha/day, respectively (Table 7.4). However, there was no significant effect of species on regrowth of tree edible biomass.

Species, stem diameter and their interaction had no significant effects on pasture regrowth (Table 7.4).

Total biomass regrowth (tree + pasture) was affected by stem diameter ($P < 0.0267$)(Table 7.4). The treatment involving trees from 35 mm stem diameter (14 kg DM/ha/day) had higher total regrowth than those from 10 mm stem diameter (4 kg DM/ha/day), but was similar to those trees established from 25 mm stem diameter (8 kg DM/ha/day).

Table 7.4 Effect of grazing and stem diameter on regrowth of edible biomass after 79 days.

Species	Stem diameter (mm)	Edible biomass regrowth (kg/ha/day)		
		Pasture	Tree	Total
Willow	10	2.5	1.8	4.2
Willow	25	4.0	1.3	5.2
Willow	35	7.9	7.7	15.6
Poplar	10	3.6	0.1	3.7
Poplar	25	6.3	4.9	11.1
Poplar	35	5.7	7.0	12.7
SEM (S*D)		3.2	1.0	3.5
Variable		Probability		
Species (S)		0.8586	0.6377	0.7620
Stem diameter (D)		0.4224	**0.0002**	**0.0267**
S*D		0.7112	0.0515	0.3852

7.4 Discussion

7.4.1 Effect of sheep grazing on willow and poplar.

Sheep grazing had no effect on tree damage to willow and poplar at any stem diameter. The average damage to main stems was 0.7% and 2.3% for willow and poplar, respectively. Broken main stems were observed at the base of trees, which resulted in tree death, particularly for those trees established from 10 mm diameter stems. The mean percentage of trees with branch breakage was 0.5%, which indicated that willow and poplar can withstand sheep grazing without serious consequences. This was supported by Sharrow *et al.* (1992b) who found only 1-2% of Douglas fir (*Pseudotsuga menziesii*) had branch breakage or other types of mechanical injury from sheep browsing. Leaning trees were observed, but this did not have any effect on tree survival or growth. Tree lean may be due to sheep rubbing against them during grazing.

Willow and poplar are very tolerant of leaf and twig browsing by sheep provided that the main stem is left intact. The effect of sheep grazing on tree mortality was small being 0-2% for willow and 0-4 % for poplar. Most tree death was related to main stem breakage at the base of trees particularly those established from 10 mm diameter stems, although some of them regrow. According to Sharrow *et al.* (1994), damaged shoots or stems should be pruned

as soon as they are identified to ensure trees regrow. Experience from many authors has also found livestock browsing (Sharrow *et al.* 1992a) and defoliation (Osman & Sharrow 1993) do not constitute a significant risk to the survival of planted trees. This experiment clearly demonstrated that grazing by sheep was not a major determinant of tree mortality.

7.4.2 Utilisation by sheep of willow and poplar established from different diameter stems

Grazing by sheep resulted in net utilization of 221 kg DM/ha to 537 kg DM/ha for willow and 287 kg DM/ha to 544 kg DM/ha for poplar. Higher % utilisation of willow established from 10 mm diameter stems than 25 mm or 35 mm diameters was probably because of higher available edible biomass that could be browsed by sheep compared to thicker diameter stem which was higher in non-edible biomass. Another factor that influenced the low edible biomass from 25 mm and 35 mm diameter stems was that edible biomass above 1.3 m was cut at the start of the experiment. Utilisation of poplar by sheep was higher in 35 mm diameter compared to trees established from thinner stems. One of the factors contributing to higher intake was the succulent shoots of poplar which are always greater than 5 mm. Some shoots less than 7 mm are soft and suitable for browsing. The utilisation of tree biomass of willow ranged from 34 to 41% for 25 mm and 35 mm diameter stems, respectively, which was comparable to the 32% to 43% found by Douglas *et al*. (2003). The results suggested that willow and poplar are palatable to sheep and can be used as supplementary fodder during times of low pasture production and quality, for example, during summer drought.

Higher utilisation of pasture occurred under willow and poplar trees established from a stem diameter of 10 mm than from 35 mm. This might have been because trees from 35 mm diameter stems had larger canopies which influenced pasture production and quality. Utilisation of understorey pasture by sheep ranged from 18% to 41% under willow and 30% to 42% under poplar. Results for willow were similar to those estimated in Wairarapa at 37-52% (Douglas *et al*. 2003).

The percentage of tree eaten by sheep compared to total biomass production in the willow/pasture system was higher from trees established from 35 mm diameter stem than 10 mm diameter stem. The higher utilisation of trees from thick stems (35 mm diameter) in the tree/pasture system may be because of the low total herbage production, contributed by low understorey pasture production. The percentage of tree dry matter eaten in the experiment ranged from 21% to 46% and 18% to 34% for willow and poplar, respectively, which was higher than the 2 to 18% reported by Douglas e*t al*. (2003).

7.4.3 Effect of sheep grazing and stem diameter on regrowth of edible biomass

Trees established from 35 mm diameter stems had higher regrowth than those established from 10 mm diameter stems. The higher regrowth could have been contributed by higher carbohydrate reserves in thick stems compared to thinner stems. Because of high energy content, large stems tend to produce more roots, enabling absorption of more water and nutrient and hence higher growth. The result was supported by the strong correlation between physical size of cutting and poplar growth (Bowersox 2001). The slow regrowth of trees was possibly because of (i) low rainfall during February to May 2005 (ii) and cold weather during autumn. According to Osman e*t al*. (1993), canopy area and basal diameter decreased as defoliation intensity increased with 50% defoliation of Douglas-fir reducing diameter growth 1 to 6.5% compared to the control. In this trial, higher utilisation ranged from 34 to 78% with a mean of 54%, which may be one of the reasons for slow regrowth of willow and poplar. Further study is required to determine the effect of grazing on regrowth biomass of trees in spring. Low pasture regrowth ranging from 2.5 to 7.9 kg DM/ha/day with a mean of 5.0 kg DM/ha/day, may also be due to the low rainfall and cold weather in autumn. Low pasture growth in autumn has been reported by many authors such as McNamara (1992) and Greenwood e*t al*. (1981).

Total regrowth of biomass was higher from tree/pasture systems involving trees established from 35 mm diameter stems than 10 mm stems. The higher regrowth may be because of the higher light interception received by

understorey pasture after tree browsing, that encourages pasture to regrow. This was supported by Hawke *et al*. (1997) and Pollock *et al*. (1994) who found herbage yield of pasture under *Pinus radiata* decreased as crown density increased. A similar result was also found for a poplar/pasture system studied by Guevara-Escobar (1999). The second reason for higher regrowth of trees established from 35 mm diameter stems might be because of higher water and nutrient absorption because of higher root biomass, leading to higher total edible biomass.

7.5 Conclusion

Sheep grazing and diameter of stems used to establish willow and poplar had no effect on tree damage (main stem or branch broken, and tree leaning) and tree mortality. Tree mortality was less than 4% for all stem diameter treatments.

Willow trees established from stem cuttings of 10 mm diameter had higher tree utilisation (70% - 537 kg/ha) than those established from 35 mm and 25 mm diameter stems (41% - 332 kg/ha and 34% - 221 kg/ha, respectively). In contrast, utilisation of poplar trees established from 35 mm diameter stems (78% - 544 kg/ha) was higher than that of trees established from 10 mm (55% - 480 kg/ha) and 25 mm diameter stems (47 % - 287 kg/ha).

Trees established from stems of 35 mm diameter produced higher tree and total edible biomass regrowth.

The results indicated that sheep grazing had negligible effects on willow and poplar tree survival and growth and that both species can be browsed during periods of pasture shortage such as in summer drought.

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8 GENERAL DISCUSSION AND CONCLUSIONS

CONTENT

8.1 Introduction

Low pasture quality during summer droughts prompts farmers to find alternative or supplementary fodder sources for their livestock (Charlton *et al*. 2003; Kemp *et al.* 2003; Olsen & Charlton 2003). An initial experiment to improve animal feed production by incorporating willow with pasture resulted in low survival of willow trees during a summer drought (Experiment 1 - Chapter 3). In addition to severe drought during 2002, thin stems could have contributed to the low survival. The results from Experiment 1 suggested that further experiments were required on stem cutting dimensions and the sensitivity of willow to soil water deficits to better define plant material and growing conditions required for the successful establishment of willow browse blocks. Efforts to improve tree survival and biomass production were focused on the effect of stem diameter and stem length in Experiments 2 (Chapter 4) and 3 (Chapter 5), respectively. In order to determine the best pasture management that can conserve soil water, competition between tree and understorey pasture was examined in Experiment 4 (Chapter 6). The effect of sheep grazing on tree damage and survival was determined in Experiment 5 (Chapter 7). This chapter relates to the thesis objectives and addresses the implications of the results to farmers and other stakeholders.

8.2 Tree establishment

Soil water content during the first growing season affected tree survival. Higher survival of willow and poplar established in 2003/04 in Experiments 2 (Chapter 4) and 3 (Chapter 5) was aided by higher rainfall and soil water content, compared with low rainfall and soil water content during summer 2002/03 (Experiment 1) when willow tree survival was relatively low. Although pasture managements such as mowing and herbicide application were implemented to reduce understorey competition, they were not effective in conserving soil water during drought, resulting in low tree survival. Previous research also found that limited soil water content influenced willow establishment (Hathaway 1986) and growth (Pezeshki *et al.* 1998).

The mowing and herbicide treatments were used primarily to create different levels of understorey pasture competition rather than as practical solutions to controlling understorey pasture. Nevertheless, Gallant NF (0.25 kg a.i. ha^{-1} haloxyfop (R-Isomer) and 0.87 kg a.i. diethyleneglycol), although expensive, was effective in killing the grass species in the pasture and was found to be safe to use over young Tangoio and Kinuyanagi willows in the Experiment 1 and in a preliminary test before the experiment.

The size of stem cuttings (diameter and length) also influenced willow and poplar survival. Vertical planting of thick stems and intermediate size stems (35 mm and 25 mm diameter, respectively) of both species gave higher survival than from thin stems (10 mm) which suggested that thick stems had higher nutrient reserves (Hoag 2004). The innovative approach of establishing browse blocks with stems planted horizontally has potential if longer stems are used, in conjunction with effective weed control. Without effective weed control for the first 6 months, new shoots from horizontal stems will not be able to compete with rampant weed growth during good growing conditions.

Significant interactions between tree species, stem length and planting depth influenced shoot emergence of horizontally planted stems of willow and poplar (Experiment 3- Chapter 5). Stems of willow and poplar of 600 mm and 200 mm length planted horizontally at 50 mm depth, successfully established multiple shoots. Higher shoot emergence from planting horizontally at 50 mm depth compared to 100 mm depth may be related to lower soil aeration, and lack of adequate oxygen and light. It was likely easier and faster for the shoots to access light when growing from 50 mm compared to 100 mm depth. Also, it is probable that with reduced light and energy, newly emerged shoots were weak and unable to penetrate through the 0-100 mm soil profile. For establishing browse blocks, it is recommended that farmers plant stem cuttings of 200-600 mm length at a depth of 50 mm.

8.3 Growth and biomass production of willow and poplar.

The main objective of Experiments 2 (Chapter 4) and 3 (Chapter 5) was to determine the effect of stem diameter and stem length on establishment and

biomass production of willow and poplar. The hypothesis was that thick, long stem cuttings increase shoot growth and biomass production, and the results of this thesis supported the hypothesis. Douglas *et al*. (2003) found longer stems produced plants with higher total and edible dry matter. It is recommended that farmers use vertically planted thick stems (35 mm diameter) for higher growth and biomass production. However, farmers interested in establishing willow and poplar horizontally are encouraged to use long stems (600 mm) planted at 50 mm depth for higher biomass production. Farmers can also use intermediate sized stem cuttings for low cost establishment, because these planting materials also showed good performance. Higher edible and total DM from vertical compared to horizontal planting indicated that vertical planting is the best method for achieving high biomass production.

Thick stems (35 mm diameters) produced higher root DM than thin stems (10 mm diameter) (Experiment 2 - Chapter 4). Higher root DM from thick stems may increase absorption of soil water and nutrients (Zierke 1994) leading to higher shoot biomass production. A strong relationship between (i) root DM and edible DM and (ii) root DM and total shoot DM, indicated that thick stems with higher root DM influenced shoot growth and biomass production. Heilman *et al*. (1994) found a positive relationship between above-ground weight and the weight of first order roots of hybrid poplar (*Populus trichocarpa* x *P. deltoides*). Similarly with horizontal planting (Experiment 3 – Chapter 5) the 600 mm long stems produced the highest root DM, leading to higher growth and biomass production.

The reason for planting thin stems (Experiment 2 – Chapter 4) and short stems (Experiment 3 - Chapter 5) was to reduce the cost of establishment of browse blocks. However, the reduced growth and biomass production from using thin stems (10 mm diameter) (Experiment 2) and short stems (50 mm) (Experiment 3) showed that this approach is riskier than using thick and long stem cuttings. Although thick stems (35 mm diameter) are usually more expensive than thin stems, the greater biomass produced by plants grown from relatively thick stems may compensate for the start-up cost of establishment.

For the browse block establishment smaller stems for planting are required compared to those used for soil conservation in erodible pasture country due to the high plant population and relatively short tree height needed for browsing. The smaller size planting materials used were byproduct of poles produced by nurseries (3.0-3.5 m long, 30-40 mm diameter) for soil conservation planting. The top (thinner) parts and branches of poles were waste material generally used for composting and mulching in the nursery. The aim was to make efficient use of these unwanted branches and produce edible browse by planting them in browse blocks to supplement sheep nutrition particularly during drought. The research successfully showed that using these waste stems for producing fodder has potential for increasing fresh fodder in dry summers. Cost-benefit analyses with various stems size needs to be conducted by an economist for cost comparisons and guidelines for the growers interested in establishing willow and poplar for fodder blocks. The first economic analysis of willow browse blocks established specifically for fodder was conducted by Stantiall (2006) for a case study farm in Wairarapa where it was found that the cost of establishment was NZ $ 8570/ha (NZ $ 6320/ha if the cost of labor is excluded).

Pasture management had an effect on willow shoot growth and biomass production in the willow-pasture agroforestry systems (Table 8.1). Trees in the mowing and herbicide treatments had relatively higher survival and growth (height, shoot number, shoot length and canopy diameter) than the unmanaged pasture in the control treatment. However, higher edible and total biomass production was found for the mowing treatment than the minimum herbicide (once/season) and control (no weed control) treatments because there was a similar mass of understorey pasture in the herbicide and control treatments. The higher biomass production by the mowing treatment suggested that control of the understorey pasture and weeds during the establishment season is vital. The most practical way to control understorey pasture during establishment still requires development but spraying with glyphosate and hard grazing before the trees are established is important. Mowing or the use if herbicides in the first season are likely to be impractical or too expensive for most browse blocks, and early grazing severely damages the establishing tree.

Tree growth and above-ground biomass production were also influenced by rainfall. Lower edible and total shoot DM production were found in Experiment 1 (Chapter 3) than in Experiments 2 (Chapter 4) and 3 (Chapter 5), probably because there was lower average rainfall during summer (Figure 3.1) in Experiment 1 than in the later experiments. Successful establishment of willows and poplars will always be subject to overcoming possible summer droughts within several months of planting. However the early planting of thick stems coupled with effective control of the understorey pasture will decrease the risk of establishment failure.

Table 8.1 Summary of the effect of pasture management on willow growth and biomass production in a willow-pasture agroforestry system.

Parameters	Pasture management
1. Willow growth and biomass production;	
a) Survival rate - ↑	Mown=Herbicide>Control
b) Tree growth:	
i. Height ↑	Mown=Herbicide>Control
ii. Shoot number ↑	Mown=Herbicide>Control
iii. Shoot length ↑	Mown=Herbicide>Control
iv. Canopy extension:	
- in-row canopy ↑	Mown=Herbicide>Control
- inter-row canopy ↑	Mown=Herbicide>Control
c) Edible and total biomass ↑	Mown>Herbicide>Control

Note: Control – no weed control.

Herbicide – one application of Gallant NF per season.

8.4 Understory pasture management and its effect on soil water content and stem water potential

The objective of this experiment (Chapter 6) was to determine appropriate management that can conserve soil water and at the same time improve shoot growth and biomass production. During summer drought, pasture management did not have any effect on SWC. Mowing, herbicide, and control (no weed control) treatments had similar or low soil water content during summer drought that caused death of several willow shoots resulting in reduced biomass production. Pasture management had a significant effect particularly during early or mid-summer on SWC. Pasture cover with different pasture managements can help to improve SWC particularly for the grazing and control treatments through rainfall infiltration by pasture canopy and root. The grazing treatment may benefit SWC because of low competition for SWC between willow and pasture understorey root compared to control (no weed control) treatment that influenced establishment and shoot growth. A similar result was also found in Experiment 1 (Chapter 3) with higher SWC for the defoliation treatment (mowing) during early summer which may help new willow trees to produce more roots and shoots making them more able to survive during dry conditions.

Monitoring soil water deficits and stem water potentials of willow can help scientists and Regional Council officers to detect the early stages of water stress, thereby minimizing the risk of establishment failure, and maintaining growth and biomass production. Results from Experiment 4 (Chapter 6) found that pasture management significantly affected stem water potential of willow trees. Low water stress (low mean stem water potential) of willow trees in the grazing treatment suggested that this pasture management practice may be good enough to adopt in future in a willow/pasture system. For example, the higher biomass of the willow trees in the mown treatment in Experiment 1 (Chapter 3) may be because of low water stress and higher SWC. The strong relationship between (i) SWC and stem water potential and (ii) stem water potential and soil water deficit, could be useful for predicting irrigation required particularly during summer droughts.

8.5 Effect of sheep grazing on establishment of newly planted willow and poplar.

The purpose of allowing sheep to browse young willow and poplar trees in their second growing season was to determine the effect of tree damage by sheep on subsequent survival and growth. The results clearly demonstrated that sheep grazing did not adversely affect survival of newly grown willow and poplar. There were minor problems arising from sheep grazing including some trees leaning and slight mechanical damage to branches and main stems. Tree mortality of willows and poplars was less than 4% and most deaths were of trees established from thin stems (10 mm diameter) where the main stems had broken at the base of the tree. Conroy *et al.* (1991) also found no significant effect of grazing on either willow survival or growth. Sharrow (1992) wanted to utilise understorey pasture with sheep and found no effect of their browsing on mechanical injury on Douglas fir (*Pseudotsuga menziesii*).

Plants established from thicker stem had better establishment and higher regrowth after grazing. Higher root production from thick stems (Chapter 4) was probably responsible for higher nutrient and water uptake, leading to higher shoot regrowth.

The present findings and previous studies (McCabe & Barry 1988; Douglas *et al.* 2003) showed that willow and poplar are palatable to sheep and can be used as a supplementary source of animal forage during times of pasture feed shortages e.g. summer droughts. The utilisation of shoots from trees established from thin stems (10 mm diameter) was higher than those trees established from thick stems (35 mm diameter), probably because the shoots from thin stems were relatively small and more succulent. Cattle can be introduced to willow pasture systems to improve utilisation of willow as they can browse shoots up to 8 mm diameter (Moore *et al.* 2003). Higher utilization of shoots from poplar trees established from stems of 35 mm diameter indicated that thick shoots (< 7 mm) produced by poplar are suitable for sheep browsing.

8.6 Future research needs

Further research is required on tree survival, growth and biomass production of willows and poplars. This research needs to focus on:

i. Frequency and time of herbicide applications. Based on the results of Experiment 1, herbicide applied once per season, in mid December, did not effectively control pasture growth. Current herbicide recommendations either result in the complete removal of the pasture understorey or in the pasture recovering too quickly and strongly competing against the establishing trees. There is, therefore, an urgent need to determine the optimum time and frequency of herbicide application required to effectively control but not prevent the recovery of pasture growth in tree-pasture blocks established by vertical and horizontal planting of poplar and willow cuttings.

ii. Further research is required for stem cuttings established by horizontal planting, particularly for short stems (50 mm lengths) planted at 50 mm depth, with respect to pasture control methods (manual vs herbicide) and type of herbicide that give higher survival, growth and biomass production during the first year of field establishment. Successful establishment of short stems is important to ensure availability of cheap planting material for farmers to establish willow and poplar in browse blocks or in areas that require dense planting for soil conservation.

iii. Water requirements and effect on growth and biomass production. Experiment 1 showed that a dry season adversely affected shoot growth and biomass production. Therefore it is important to determine the minimum requirements of water (soil water content) for willows for satisfactory survival and biomass production.

iv. Average height that a browsing tree should be maintained. As willow and poplar grow very fast during favourable weather conditions, there is a need to determine the optimum height at the end of the growing season

for the continuing use of trees in a browsing/grazing system in subsequent seasons. An experiment should be conducted which determines the effect of a range of cutting heights at the end of the growing season. Optimum cutting height should be based on livestock type and age, and vigour of trees, particularly with respect to regrowth potential.

v. Further research is needed on horizontal stem planting (Experiment 3) particularly on the aspects of stem diameter, carbohydrate reserves, number of buds per stem, and planting technique (to improve soil aeration), as they affect survival and biomass production of willow and poplar.

vi. The technique of root sampling (Experiment 4) needs refinement particularly in the aspects of soil core size and depth, and sampling designs such as circle, half and quarter circle around the trunk. This is important to determine the distribution of roots, which influences water and nutrient competition in agroforestry systems.

8.7 Proposed post-establishment of willow and poplar

Weeds should be controlled during the first year of field establishment of willow and poplar. Uncontrolled weeds will reduce willow and poplar tree growth by 50 % and edible dry matter yield by 20 % of willow and poplar in a short rotation system compared to weed-free conditions (Macpherson 1995). During the 1-1.5 months (middle of September) after field planting, when shoots emerge, weeds should be controlled to reduce competition. Manual weed control or spot spraying are needed. Selective herbicides for weeds around willow and poplar trees such as Gallant NF (0.25 kg a.i. ha^{-1} haloxyfop (R-Isomer) and 0.87 kg a.i. ha^{-1} diethylene glycol), which is selective for grasses, should be considered to ensure herbicide does not affect growth of the trees. Use of glyphosate requires caution because even a low concentration of glyphosate drift severely damages young willow and poplar (Macpherson 1995). Another herbicide application should be conducted in November after manual weeding in mid-September. Delayed spraying can result in rampant growth of weeds,

especially in December, due to higher temperatures, which decreases willow and poplar growth.

Willow sawfly (*Nematus oligospilus*) attacked foliage of willow clone 'Tangoio' during summer. Early detection and control of this insect pest are important to make sure willow growth and biomass production are not compromised. Insecticide such as Orthene (195 g/l acephate plus 346 g/l ethylene glycol) effectively kills the sawfly.

8.8 Conclusion

The research showed that poplar and willow trees established from thick stems (35 mm diameter) planted vertically, produced higher shoot growth and higher above- and below-ground biomass than trees established from thin (10 mm diameter) and intermediate-sized (25 mm diameter) stems. Trees developing from stems of 25 mm and 35 mm diameter also had higher survival than those from small stems (10 mm diameter). Trees established from stem lengths of 600 mm planted horizontally at 50 mm depth also had higher survival, growth and biomass production than those established from short stems (50 mm). Stem cuttings planted vertically produced higher shoot biomass than stem cuttings planted horizontally. The results suggested that farmers should establish willow fodder blocks using thick stems (vertical planting) and long stems (horizontal planting) for higher growth and biomass production.

Pasture management significantly influenced shoot growth and biomass production of establishing willow trees in willow-pasture systems. Mowing pasture resulted in higher biomass production compared to one herbicide application or no weed control. Willow clone 'Kinuyanagi' produced higher edible DM and total shoot DM than clone 'Tangoio' under dry conditions.

From 20 September 2004 to 21 April 2005, pasture management with varying treatments (grazing, herbicide and no weed control) had a significant effect on SWC during early/mid summer 2004/05. Grazing and control (no weed control) treatments had higher SWC during these periods. Higher SWC in the grazing treatment provided adequate moisture to develop roots and shoots that made

plants more tolerant of oncoming dry periods with respect to better establishment and shoot growth. There was no effect of pasture management during wet (spring 2004) and dry (late summer/autumn 2005) conditions.

Willow trees in the grazing treatment had lower mean stem water potential or lower water stress than those in the herbicide and control (no weed control) treatments. This result indicated that grazing treatment is a better approach for maintaining low water stress of willow in a willow-pasture system compared to herbicide and control treatments. To ensure willow growth is not affected by water stress (water deficits), it is possible to predict water requirements of trees particularly during dry conditions by using relationships between (I) SWC and stem water potential and, (II) stem water potential and soil water deficit.

Sheep grazing and variation in stem diameter of planted cuttings of willow and poplar had no effect on tree mortality and the degree of damage to trees, assessed with respect to damage of the main stem and breakage of branches, and the amount of tree leaning. Thick stems (35 mm diameter) produced higher shoot regrowth resulting in greater total biomass after sheep grazing. Since sheep grazing had negligible effect on young trees, it is suggested that they can be browsed during summer drought, when pasture production is low and of poor quality.

8.9 References

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