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Interactions between widely spaced young poplars (*Populus* spp.) and the understorey environment

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Abstract Silvopastoral systems involving poplars are common to rural landscapes in many parts of New Zealand. The effect of widely spaced trees of *Populus nigra* × *P. maximowiczii*, aged 8–11 years, on the surrounding micro-environment in a tree-pasture system was determined over 3 years at a southern North Island hill country site. Relative to open (unshaded, no trees) pasture, understorey pasture received 33% less radiation while radiation on the north side of trees (North) was similar to that on the south side of trees (South). Around one tree, soil temperature averaged 14.9°C annually on the North and 13.8°C on the South. Soil water content was highest in spring and winter (0.35–0.39 m^3 m^{-3}) and lowest in summer and autumn (0.21–0.26 m^3 m^{-3}), and differences occurred between plots in open pasture and those beneath trees in all seasons except spring. Soil water content of tree aspects differed slightly (<10%) in summer (South > North) and autumn (North > South), but not in spring and winter, when contents were similar. Soil pH was 0.2 units higher beneath trees than in open pasture in one of 2 years. Concentrations of Ca, K, Mg, P, and S were similar in tree and open environments. The study results complement those collected for mature trees, and will be useful in developing tree-pasture models.

Keywords Hill country · Shade · Silvopastoral system · Soil conservation · Soil water content

Introduction

Poplars (*Populus* spp.) are an integral part of many New Zealand pastoral hill country landscapes, where they have been planted for more than 30 years, primarily to prevent or reduce soil erosion mediated by surplus soil water (Wilkinson 1995). These deciduous tree species provide other benefits including shade and shelter for grazing sheep and cattle, supplementary forage (prunings and leaf fall) particularly in late summer/early autumn, landscape enhancement, and timber production.

The effectiveness of poplars for controlling erosion on hill farms and their additional, mostly long-term

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benefits, have encouraged increased planting, particularly of new, commercially available, disease-resistant clones. For example, across the four Regional Councils in the southern North Island, unpublished records suggest recent planting of about 80,000 poplar poles/year (D. Cameron, G. Eyles, L. Grant, K. Rooke, pers. comm., 2003) and this trend is expected to continue. However a decision to plant poplars requires a rigorous assessment of the risk of leaving a site unplanted and therefore more susceptible to erosion and a consequent loss in productive capacity, versus the potential costs and benefits of planting.

Mature poplars can have a significant effect on the surrounding aerial and soil environments when the canopy is at or near closure. Compared with areas without trees, Guevara-Escobar et al. (1997) found that photosynthetically active radiation beneath a closed canopy in spring and summer was reduced by 40–90%, soil temperature was 0.6–3.3°C lower, and soil water content was reduced by up to 0.14 m^3 m^{-3}. At several sites, soils were 0.5–1.2 pH units higher beneath trees than in the open (Guevara-Escobar et al. 2002). Younger, widely spaced poplars can also markedly influence aerial and soil environments, depending on factors such as site and tree age (Hurst et al. 2000; Douglas et al. 2001). More information on poplar–pasture–soil–water interactions is required to produce robust models that predict the effects of poplars over their lifetime. Such models can be used to appraise the temporal and spatial consequences of planting trees for soil conservation and management practices. A model predicting pasture production, based on light distribution patterns beneath and around trees of different ages, has been produced (Dodd et al. 2004).

This study aimed to determine the effect of intermediate-aged (8–11 years), widely spaced poplars on: (1) radiation, soil water, and soil temperature patterns; and (2) soil pH and nutrient concentrations. The agronomic performance of the pasture understorey (existing sward and two introduced mixtures) is reported in a companion paper (Douglas et al. 2006).

Materials and methods

Site

The trial was conducted on a commercial sheep and beef cattle farm in the Pohangina valley, 34 km north east of Palmerston North, in the southern North Island of New Zealand (latitude 40°10′ S, longitude 175°45′ E, 260 m a.s.l.). The soil is a Raumai hill soil (weakly leached, weakly gleyed palli-fluvic), a sandy loam, which is free-draining and moderately fertile (pH=5.6–5.7; Olsen P=15–20 mg/kg soil). Parts of the farm are fertilised annually with 200 kg/ha diammonium phosphate, with sulphate additive. The climate is temperate with mean daily air temperature ranging from 7.9°C in June (winter) to 17.4°C in January (summer). Average annual rainfall for the site is 1200–1300 mm (Rijkse 1977).

The site was in a 10 ha paddock which had unevenly spaced (5–20 m apart, or 25–400 trees/ha), unpruned poplar (*Populus maximowiczii* Henry × *P. nigra* L.) trees aged 8 (in 1997) to 11 years, on 5–10° slopes in gullies facing east and south-east. Approximately 20% of the site was covered by trees. In October 2000 the trees had a mean height of 17.4 (s.d.=1.3) m, stem diameter at breast height (1.4 m) averaged 31.9 (s.d.=5.4) cm, and individual tree crowns did not overlap. Existing pasture in August 1996 comprised 65% grass, 10% legume, 10% other species, and 15% dead matter (Douglas et al. 2006).

Treatments and experimental design

There were three pasture mixtures (Douglas et al. 2006) in three environments, arranged in three randomised complete blocks. Environments were:

1. South side of trees, which was shaded in the middle of the day when trees had full canopy (South);
2. North side of trees, which was unshaded for most of the day (North); and
3. Adjacent areas of open pasture without trees (Open).

Plots (experimental units) in all environments were located on areas of similar topography on the gentle slopes of gullies. Plots beneath trees extended 9 m from a tree along a north-south transect and were 4 m wide (2 m either side of transect), and those in Open plots were 3 × 3 m. Measurements were made directly north and south of individual trees where environmental gradients were expected to be greatest. Beginning in autumn 1997, pasture swards in all environments were grazed by sheep as part of the normal grazing management for the paddock.

Measurements

Environmental parameters

A range of parameters was measured around a nearby tree of similar size to those used in the experiment. Variables included rainfall, air temperature and relative humidity, and soil temperature at 100 mm depth. Soil temperature sensors were located 4 m either side of the tree along the north-south transect. Rainfall was measured at a position away from any likely influence of the trees. Global and diffuse shortwave (400–1100 nm) radiation were measured in the Open environment with two pyranometers (LI-200, Li-Cor, Lincoln NE), one shaded from direct radiation by a shade band. A third pyranometer measured shortwave radiation in the South environment under the shade of the tree canopy. All sensors were measured every 60 s by a datalogger (model CR10, Campbell Scientific Instruments), and hourly mean values were calculated and stored.

Irradiance in environments

In order to quantify the impact of tree canopies on solar radiation in each environment, hemispherical photographs were taken in each plot on overcast days in June 2000 after leaf fall and again during December 2000 when the trees were in full leaf. The images were scanned then analysed using Hemiview software (Delta-T Devices, Cambridge, UK). The software transforms the image into black (representing vegetation and ground) or white (representing sky) pixels. The threshold intensity that produced the best contrast between sky and non-sky pixels for several images was determined manually by comparison before and after transformation.

For each plot, a direct site factor (DSF) and an indirect site factor (ISF) were calculated for two periods—when the trees were foliated (1 October–30 May, hereafter called the "foliated period") and when the trees were leafless (1 June–30 September, "non-foliated period"). DSF and ISF are the proportions of direct and indirect (diffuse) radiation reaching the image location relative to those in a similar location but with no sky obstructions. Global site factors (GSF) were calculated by summing DSF and ISF, weighted by the relative proportions of direct and diffuse incident irradiance. Annual values for DSF, ISF, and GSF were calculated by summing values from the foliated and non-foliated periods, weighted according to the irradiance received during each period relative to the annual total irradiance.

Soil water patterns

Volumetric soil water content (m^3 water m^{-3} soil) in the tree and Open plots was determined using Time Domain Reflectometry (TDR; Topp et al. 1980). Three-pronged TDR probes were permanently installed in 1997 in North and South plots at 0–200 mm and 200–400 mm soil depths at 1, 2, 4, and 8 m from the trunk, along north-south transects. Only data for the 2 m position are presented, as this position coincided most closely with the location of pasture growth measurements (Douglas et al. 2006). In each of the nine Open plots, probes were inserted at two randomly selected positions to the same depths. From 3 March 1998 to 25 February 2000, soil water content at these locations was measured about every 2 weeks from spring to autumn, and monthly during winter. A cable tester (Tektronix 1502C Metallic Time-Domain Reflectometer) was used to determine the apparent length of the probe, from which the soil water content was later calculated.

Soil chemistry

Soil cores (0–75 mm depth) were sampled from one randomly selected position within each Open plot and the pasture sampling areas of the tree plots (Douglas et al. 2006), in January 1998 and January 2000. Samples were assayed for soil pH (1:2.5 soil:water suspension), Olsen-extractable phosphorus (P), extractable sulphate sulphur (S), and quick test concentrations of calcium (Ca), magnesium (Mg), and potassium (K), following extraction with 1 N, neutral (pH 7) ammonium acetate (Mountier et al. 1966). Total carbon (C) and nitrogen (N) were determined by combustion in oxygen at 1050°C with the resulting CO_2 being measured by infrared detection, and N_2 by thermal conductivity.

Statistical analyses

The effects of environment on DSF, ISF, and GSF during the foliated and non-foliated periods, and across the whole year, were analysed by analysis of variance. The measurement dates for soil water content in each of the 2 years were classified into seasons of spring (September–November), summer (December–February), autumn (March–May) and winter (June–August). Data for each season were pooled across years and analysed using analysis of covariance based on antedependence (Kenward 1987) using cyclical time. Split-plot in time analysis of variance, weighted for seasonal variances, was also conducted, and soil temperature and chemistry data were subjected to the same analysis, without weighting.

All data were analysed using GENSTAT (2002) and mean separation was achieved using the Least Significant Difference test at the 5% significance level.

Results

Site climate

Mean daily air temperature varied seasonally between 9 and 23°C (Fig. 1a) and mean daily air vapour pressure deficit rarely exceeded 2 kPa for most of the experimental period (Fig. 1b). Mean monthly soil temperature varied from 8.5 to 21.8°C. Soil temperature in the North (14.9°C) averaged 1.1°C warmer ($P < 0.001$) than the South (13.8°C) across the year, but differences between aspects varied considerably with month (Fig. 1a), ranging from 0.13°C in June to 2.8°C in February.

Global shortwave irradiance varied from 5 MJ m^{-2} d^{-1} during winter to 18 MJ m^{-2} d^{-1} during summer (Fig. 1c). On average, diffuse radiation constituted about 43% of global radiation at this site, varying from around 20% in summer to 60% in winter. In the South environment, irradiance was always lower than in the Open, with the difference greatest during the foliated period. Over the 3 years of measurements, irradiance on the South was 72% of that in the Open, varying between 67% during foliated periods and 92% during non-foliated periods. Mean annual rainfall at the site across the 3-year period was 983 mm (Fig. 1d), with an average of 26% falling in autumn, 29% in winter, and 27% in spring, while summer was slightly drier with 18% of total rainfall.

Irradiance in environments

Over the year, DSF, ISF, and GSF in the tree environment (mean of North and South) were lower than in the Open by 35, 32, and 33%, respectively ($P < 0.001$, Table 1). There was, however, a large seasonal influence on the difference between tree and Open environments ($P < 0.001$). During the foliated period, DSF, ISF, and GSF in the tree environment were 40–42% lower than in the Open compared to the non-foliated period ($P < 0.001$), when DSF, ISF, and GSF in the tree environment were 9–12% lower than in the Open. There was no effect of season on DSF, ISF or GSF in the Open environment.

Over the year, DSF was greater, but ISF slightly lower, in the North compared to the South, resulting in a significant ($P < 0.05$) but small difference in GSF between North and South environments (Table 1). All site factor means for both tree environments were less than in the Open environment.

In the foliated and non-foliated periods, DSF, ISF, and GSF in the North and South environments were less ($P < 0.05$) than in the Open. An exception was DSF in the North when trees were without leaves, when it was similar to that in the Open environment. In both periods, DSF was greater in the North than in the South whereas the reverse trend occurred for ISF. GSF in the foliated period was similar in both tree environments compared to during the non-foliated period when it was 8% greater ($P < 0.05$) in the North than South environments.

Soil water content

Soil water content at both depths and in each environment varied with season, being highest in spring and winter (0.35–0.39 m^3 m^{-3}) and lowest in summer and autumn (0.21–0.26 m^3 m^{-3}) (Fig. 2a, b). In autumn and winter, soil water content at 0–200 mm depth was 8% higher ($P < 0.001$) than at 200–400 mm depth, whereas in summer the reverse trend occurred with soil water content at 200–400 mm depth exceeding that at the shallower depth by 15%. In spring, soil water content at both depths averaged 0.36 m^3 m^{-3}.

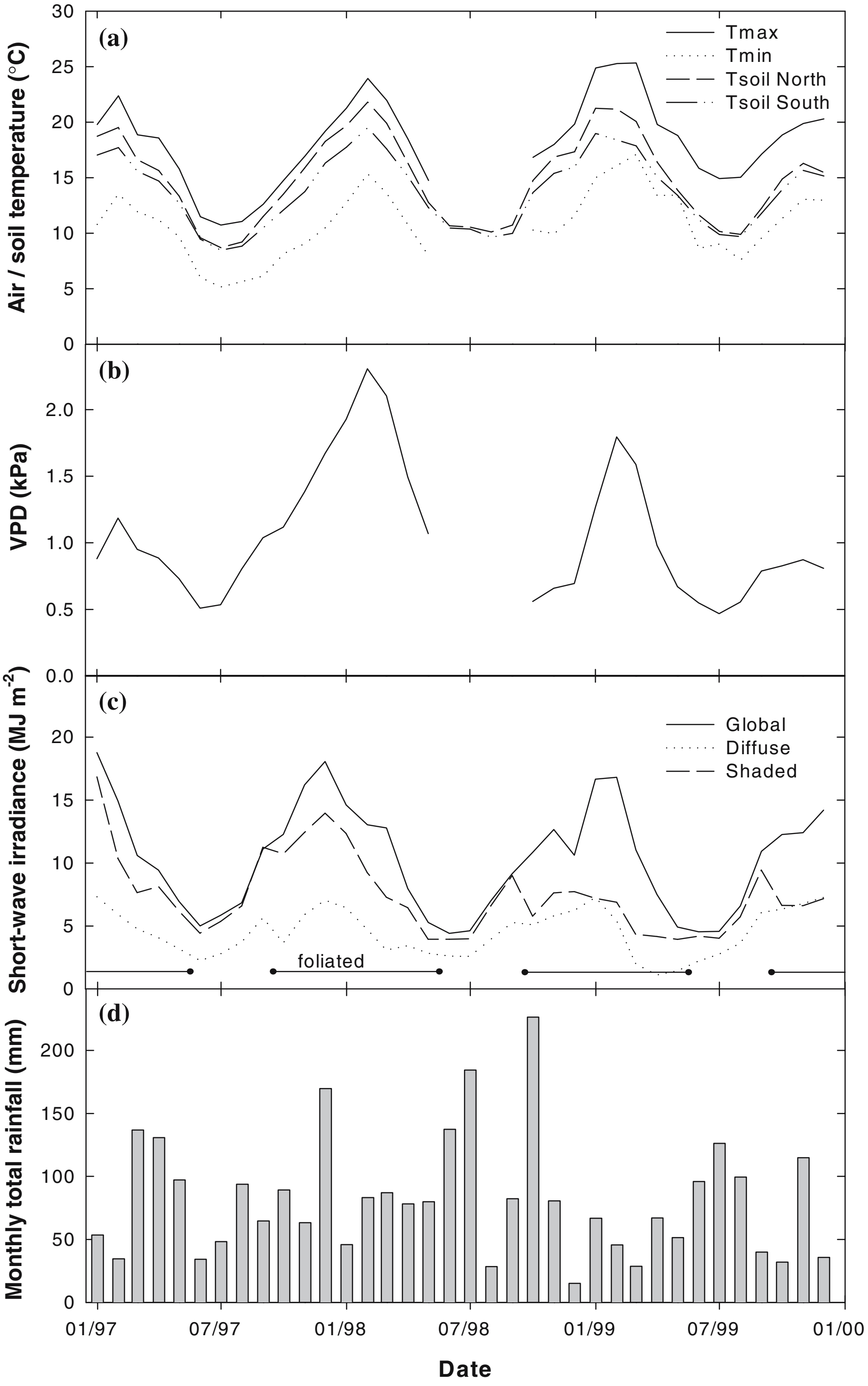

Fig. 1 Air and soil (100 mm depth) temperature (**a**), vapour pressure deficit (VPD) (**b**), short-wave irradiance (**c**), and monthly total rainfall (**d**) at the poplar tree—pasture trial site near Palmerston North, New Zealand, from 1997 to 2000

Table 1 DSF, ISF, and GSF means for North, South and Open environments during periods when trees were foliated, non-foliated and over the whole year, near Palmerston North, New Zealand

	North	South	Open
Foliated period			
DSF	0.67b*	0.35c	0.84a
ISF	0.45c	0.54b	0.86a
GSF	0.54b	0.47b	0.85a
Non-foliated period			
DSF	0.84a	0.72b	0.89a
ISF	0.85c	0.87b	0.95a
GSF	0.85b	0.79c	0.92a
Whole-year			
DSF	0.69b	0.42c	0.85a
ISF	0.56c	0.63b	0.88a
GSF	0.62b	0.54c	0.87a

*Values within rows with different letters differ at $P < 0.05$; sample size=3 for Open environment and 9 for North and South environments

Mean soil water content (averaged over both depths) ranged from 0.22 to 0.39 $m^3 m^{-3}$ beneath trees, and from 0.23 to 0.36 $m^3 m^{-3}$ in Open plots over a period of 2 years. The effect of trees on soil water content was most apparent during winter and summer. In winter, tree plots at both depths (0.39 $m^3 m^{-3}$) were 9% wetter ($P < 0.01$) than Open plots (0.36 $m^3 m^{-3}$) whereas during summer, Open plots (0.26 $m^3 m^{-3}$) had nearly 10% higher soil water content than those beneath trees (0.24 $m^3 m^{-3}$). During autumn, soil water content was similar in Open and tree plots but in spring, responses varied with soil depth. This was because soil water content beneath trees (0.35 $m^3 m^{-3}$) at 0–200 mm soil depth was the same as in Open plots, whereas at 200–400 mm depth, it was slightly lower beneath trees (0.35 $m^3 m^{-3}$) than in Open plots (0.37 $m^3 m^{-3}$).

Soil water content varied with tree aspect and season (Fig. 2a). In summer, North plots were slightly drier ($P < 0.01$) than South plots, and in

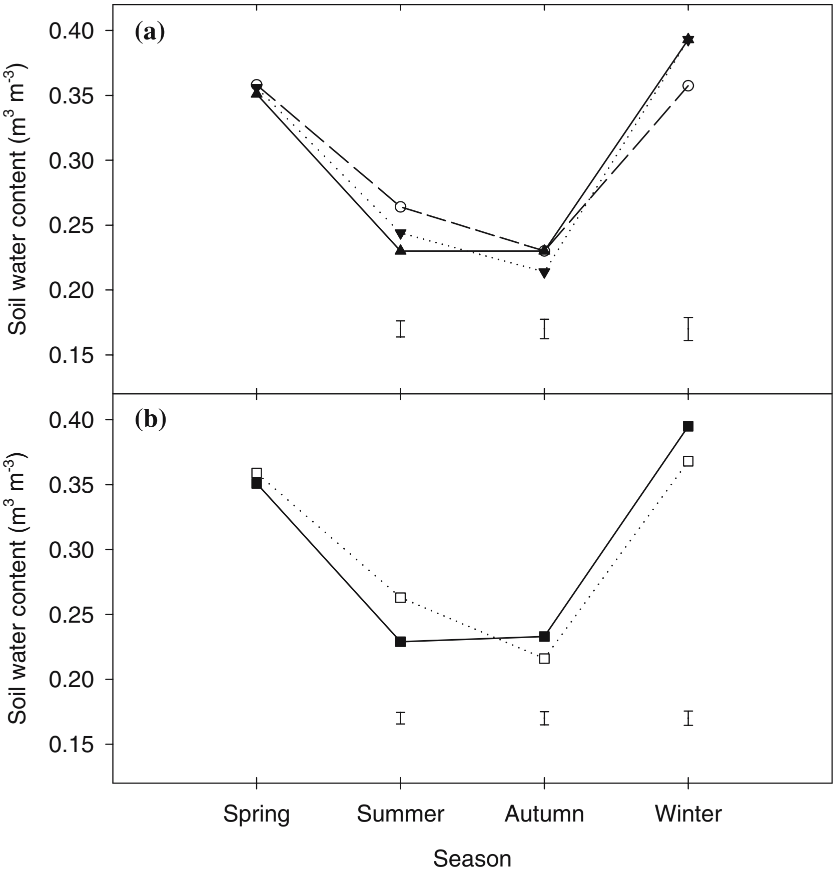

Fig. 2 Seasonal volumetric soil water content in the poplar tree—pasture system, near Palmerston North, New Zealand, averaged over 2 years: (**a**) North (filled triangle up) and South (filled triangle down) sides of trees and in the Open (hollow circle), averaged over two depths; (**b**) 0–200 mm (filled square) and 200–400 mm (hollow square) soil depths, averaged over three environments. Vertical bars=LSD at $P < 0.05$ (no significant differences in spring)

autumn, the reverse trend occurred with North plots being 7% wetter than South plots. In spring and winter, soil water content did not vary significantly between aspects.

Soil pH and macronutrient concentration

Across environments, soil pH levels in 1998 (5.64–5.71) were not significantly different whereas in 2000 they were in the order ($P < 0.05$) North (5.70) > South (5.56) > Open (5.45). Soil pH in North plots was the same in both years and contrasted with the other environments where levels in 1998 were 0.16 (South) and 0.19 (Open) units higher ($P < 0.05$) than in 2000. There were negligible differences between environments in concentration of Ca, K, Mg, P, and S. Significant between-year variation occurred for all attributes except Ca concentration, with concentrations of P and S highest in 2000, and soil pH and concentrations of K and Mg highest in 1998 (Table 2). All treatments in 2000 had similar total carbon (C; mean=4.9%), total nitrogen (N; mean=0.4%), and C/N ratio (mean=12.2).

Discussion

This 3-year study showed that widely spaced, intermediate-aged (8–11 years) poplars growing at a temperate climate, lower North Island site, had a significant effect on the surrounding aerial and soil micro-environment. The results were likely representative of many poplar–environment interactions because the parentage of the species and growth form of the trees in this study were typical of the many thousands of similarly aged poplars growing on erodible hillsides in New Zealand.

Table 2 Mean soil pH and nutrient levels at 0–75 mm depth, near Palmerston North, New Zealand in January 1998 and 2000

Year	pH[B]	OlsenP (mg/kg)	S[C] (mg/kg)	Exchangeable cations (me/100g soil)[A]		
				K	Ca	Mg
1998	5.68a[D]	10.7b	10.0b	0.5a	3.3a	1.2a
2000	5.57b	24.9a	26.1a	0.3b	3.1a	0.8b

[A] Converted “quick test” units assuming constant soil bulk density; lN ammonium acetate, pH 7

[B] Determined on a 1:2.5 soil:water suspension

[C] CaH_2PO_4-extractable SO_4–S

[D] Values within columns with different letters differ at $P < 0.05$; sample size=27

Radiation and soil temperature

The 33% lower GSF in the tree environment compared with the Open, and the marked influence of season (foliated versus non-foliated), was consistent with direct measurements of irradiance in the South environment, which were 33% lower than in the Open during the foliated period and 8% lower during the non-foliated period. These results agree with radiation measurements beneath *Populus* canopies in other studies. For large, untended, mature (>25 years) trees of *Populus deltoides* grown at a nearby site, where the canopy was at or near closure (Guevara-Escobar et al. 1997), and in plantations of hybrid poplar in the northern hemisphere (Zavitkovski 1982), photosynthetically active radiation beneath foliated trees in spring and summer was 40–90% less than in the Open.

Annual or seasonal differences in global radiation received in North and South environments were small, but the study highlighted the importance of measuring direct and diffuse components, as radiation patterns varied significantly with season. Diffuse radiation constituted more than 40% of global radiation at this site, resulting from a high frequency of cloudy days. This reflects the site location, just west of a mountain range (900–1200 m) in a predominantly westerly wind flow.

The small light gradient between North and South environments partly reflects the high proportion of incident diffuse radiation at the site because diffuse radiation is generally similar for all aspects around a tree. In addition, tree size and canopy shape strongly determine interception of direct radiation by canopy foliage. In this study tree crowns were relatively narrow and pruned to 2 m height. This meant that even during the foliated period, a significant amount of direct radiation reached the South environment during the morning and afternoon, when the sun was lower in the sky and to the east or west of the tree. During the non-foliated period, the impact of the canopy on direct and diffuse radiation is small, reducing further the difference in radiation between North and South environments. The small difference in global radiation observed between tree environments, where the greatest difference was expected, suggests that between-aspect variation in global radiation was negligible in any direction around each tree.

The often relatively high direct radiation flux on the North side of trees was probably most responsible for soil temperatures on that side averaging 1.1°C warmer than those on the South side. In a nearby study, Guevara-Escobar et al. (1997) found that beneath a small stand of mature poplars with essentially a continuous crown, soil temperature at 100 mm depth was 0.6°C (winter) to 3.3°C (summer) lower than in the open. In contrast, average soil temperature beneath *Populus deltoides* × *nigra* trees aged 10–15 years and spaced at 16–44 trees/ha, was similar to that beneath open pasture (Douglas et al. 2001). Soil temperature in the Open environment was not measured in this study but a temperature differential of 2.8°C occurred between North and South tree aspects in February 1999 (summer), which showed the significant effect that even relatively young trees can have. Part of this soil temperature differential may be due to differences in soil water content between North and South aspects. During summer, soils in North plots were drier than those in South plots, and dry soil has a lower volumetric heat capacity, resulting in a greater increase in temperature for a given radiant flux density, compared to moist soil.

Rainfall and soil water content

The mean annual rainfall of 983 mm was below the long-term average of 1200–1300 mm recorded in the Pohangina district (Rijkse 1977). This may have been partly because of variation in topography at the respective measurement sites; for example, the trial site comprised gentle gullies which were frequently sheltered, compared with areas of higher elevation and of greater expanse (J. Cousins, pers. comm., 1999).

Mean volumetric soil water content at 0–400 mm depth followed a characteristic U-shaped profile; high in spring ($0.35\ m^3\ m^{-3}$), low in summer ($0.25\ m^3\ m^{-3}$) and autumn ($0.22\ m^3\ m^{-3}$), and high again ($0.38\ m^3\ m^{-3}$) in winter. This is a typical pattern for soil water content in a temperate silvopastoral system (Yunusa et al. 1995; Guevara-Escobar et al. 1997), and was governed by site rainfall (fairly uniform from autumn until spring, and slightly lower in summer) and likely seasonal changes in pasture and tree evapotranspiration, as reported in other tree-understorey systems (Whitehead et al. 1994; McJannet et al. 2000).

At depths of 0–200 and 200–400 mm, soil beneath the tree canopies during winter was 9% wetter than in the Open plots, which was similar to earlier observations (Douglas et al. 2001). However the results contrasted with those of Guevara-Escobar et al. (1997) at a nearby site, who found that differences in soil water content (0–300 mm depth) beneath mature poplar trees and open pasture during winter were negligible. It is likely that stemflow (Jackson et al. 2000; Hurst et al. 2002) in winter accounted for the elevated soil water content beneath trees in this study, especially as the measurements were made close to the tree trunks. Soil beneath mature trees can have increased water holding capacity due to higher soil organic matter content (Young 1997), but in this study, the similar total carbon contents of soil from beneath the intermediate aged trees, and soil in Open plots, suggested that this was not a contributing factor. In summer, the approximately 10% lower soil water content of tree plots compared with Open plots was similar to differences measured in other studies (Guevara-Escobar et al. 1997, 2000; Hurst et al. 2002), and can be attributed to increased rainfall interception by the tree canopy and higher tree water use.

Tree aspects differed in their soil water content only in summer (North > South) and autumn (South > North), when contents were about 50% less than in spring and winter. Beneath mature poplars, Guevara-Escobar et al. (1997) found that north plots ($0.33\ m^3\ m^{-3}$) were drier than south plots ($0.35\ m^3\ m^{-3}$), but this study also showed that the relationship between the aspects varied with season. The relatively dry North aspect in summer probably arose because of increased evapotranspiration by understorey pasture on the North versus the South side of trees due to slightly greater irradiance. Asymmetrical tree canopy and root development could also affect water interception and uptake, however the absence of a significant aspect effect in spring, and the location of the trees in two differently orientated gullies, suggests that this was unlikely.

The significant seasonal variation in soil water content with depth across the tree and Open environments was the dominant feature of the results, but they also showed that vegetation type (tree versus Open pasture) had an important influence on soil water content in summer (Open > tree) and winter (tree > Open). Differences in vegetation cover may also explain the results in spring when soil water content at 0–200 mm depth was similar beneath trees and in Open plots, whereas at 200–400 mm depth, soil beneath trees was drier than under Open pasture. Poplar tree roots explore similar and deeper parts of the soil profile than measured here (Puri et al. 1994; Burgess et al. 1997), and they could have accounted for greater depletion of soil water in the 200–400 mm zone as the growing season started and progressed.

Soil chemistry

Soil pH was about 0.2 units higher beneath trees compared with Open plots in January 2000, when the trees were aged 11 years. This was smaller than the 0.5–1.2 pH unit increase measured by Guevara-Escobar et al. (2002) in soil 0–75 mm beneath poplars aged 5 years at one site and 15 to >25 years at nine sites. The increase in pH is the opposite of the effect commonly observed in radiata pine-pasture agroforestry plantations (e.g. Hawke 1993; Parfitt et al. 1997), and has been attributed mainly to changes in soil chemistry that arise due to annual cycling of macronutrients, from the lower horizons or subsoils explored by the poplar roots, to the soil surface via leaf litter and decomposition (Guevara-Escobar et al. 2002).

The development of differences in soil pH between tree and Open environments from 1998 (no difference) to 2000 (tree > Open), in the same plots, could be because of a number of factors. These include nutrient cycling effects becoming more apparent as the trees aged and increased in crown size, and variation in soil sampling positions, which can account for quite large variability in a range of soil chemical attributes in New Zealand hill country, even over short (< 1 m) distances (Morton et al. 2000).

The negligible effect of environment type on soil macronutrient (P, S, K, Ca, and Mg) concentrations was in agreement with the findings of Guevara-Escobar et al. (2002) for poplar trees aged 5 years, compared with open pasture. These workers also found that for trees aged 29 and 40 years, extractable sulphate S and Olsen P were generally not significantly higher beneath trees than beneath open pasture. This study was confined to intermediate-aged trees at one site, but as the trees age, higher concentrations of Ca, K, and Mg could develop beneath the trees relative to Open pasture, as found consistently for mature trees at nearby sites (Guevara-Escobar et al. 2002). The significantly higher concentrations of P and S in 2000 compared with in 1998 were undoubtedly because of fertiliser application, which occurred at least once in the trial area. Throughout the trial, slightly more sheep were observed grazing Open plots than tree plots, but the effect of this on the results for the two environments was uncertain.

Conclusions

The results of this study showed that the presence of intermediate-aged (8–11 years), widely spaced poplars had a significant effect on the hill pasture micro-environment, changing the soil water content, altering the irradiance distribution, modifying soil temperature, and influencing the soil pH. This information complements that obtained for mature poplar stands at or near canopy closure. The findings suggest that individual trees dramatically affect the micro-environment from shortly after planting through to maturity, which has important implications for soil conservation e.g. soil water control, and recommendations for plant spacing and tree management.

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