An investigation of space-planted *Populus×euramericana* 'Veronese' trees for predicting influences of tree size and shading on understorey pasture production

A dissertation presented in partial fulfilment of the requirements for the degree Bachelor of Science in Agricultural Science at Massey University, Manawatu

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Abstract

Pasture exclusion cages, PAR light sensors and TDR moisture probes were installed at two experimental units, with similar climate characteristics and space-planted distances to measure understorey pasture production. The raw data was then incorporated with NIWA's virtual climate station network and the parameters used to develop a modelling system.

Pasture production was significantly decreased within both experimental units in comparison to open pasture, with a maximum of 89% that of open pasture growth levels found at Site A. Pasture production was predominately influenced by the proportion of light able to filtrate through the canopy cover, decreasing with tree age as leaf and woody material increased. Soil analysis found that carbon and nitrogen levels were greater in the open pasture system, however, pH levels were substantially greater within the experimental units.

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1.0 Introduction

Trees of the genus *Populus* are one of the most successful hill country erosion control conservation trees in New Zealand. Space planting of poplar trees for the sustainable management of pastoral land has numerous benefits from stabilising land masses through drying out and binding of the soil, to increasing the soil nutrient status within the immediate vicinity of the tree and root system, to providing shelter and forage material to livestock in dire situations (Donald *et al.*, 1996; Ekanayake *et al*, 1997; Wilkinson, 1999; Guevara-Escobar *et al*, 1998; McIvor *et al*, 2011). When used effectively, poplar trees have the ability to reduce soil erosion from between 50-95% (Hicks, 1992, Douglas *et al.*, 2011), and this reduction increased with tree size (Douglas *et al.*, 2011).

With New Zealand's key export industry being the agricultural sector, animal production on hill country farms is driven by the ability to graze on pastoral land. The shelter and shade provided by conservation trees directly impacts upon pasture production, with previous research indicating a reduction in understorey pasture growth from 20-40%, dependent upon planting distances and the surrounding environment (Gilchrist *et al.*, 1993; Guevara-Escobar, 1999; McElwee *et al*, 2000; Wall *et al*, 2006).

Field-based research on the impact poplar trees have on understorey pasture production has predominately been conducted around young and undeveloped material up to 8 years or mature trees greater than 25 years old. Tree stocking rates with regards to pasture production have also been predominately based around agroforestry blocks and stands in which stocking rates far exceed that employed in poplar plantings for erosion control e.g. 250 stems per hectare (sph) c.f. 25-50 sph. This lack of information is a major hindrance to farmers adopting tree planting programmes when considering sustainable land management options, although it has been widely argued the costs and benefits to integrating and managing space planted poplars favours having conservation trees.

The main objective of this dissertation is to provide the farming community with reliable and applicable information on the effects on pasture production surrounding poplar-pasture systems within a hill country setting. The experiment reported in this dissertation was to determine the impact space-planted poplars of different ages have on the understorey pasture growth compared with open pasture. Possible causes for the change in pasture production levels could be the proportion of light transmission through the canopy cover as well as soil moisture and the physical and chemical characteristics of the soil as the poplar trees increase in age. The leading study research question is an investigation of space-planted *Populus×euramericana* 'Veronese' trees for predicting influences of tree size and shading on understorey pasture production.

Measurements were obtained from the poplar overstorey, the pasture understorey and the physical environment within the experimental unit (EU) and the open pasture.

The first section of this dissertation reviews the available literature relevant to this field of study and is divided into three key sections; Literature associated around the benefits and contribution poplars have made to erosion-prone hill country followed by the review of literature on below-ground influences and subsequently above-ground impacts on understorey pasture production. The methodology, findings and interpretation of the investigation carried out to attend to these research gaps are presented. The discussion of findings also identifies further research gaps and research questions.

2.0 Literature Review

New Zealand's predominately mountainous and hilly landscapes, coupled with the dynamic tectonic setting and constantly variable climate are the main contributing factors surrounding the environmental issue of sustainable hill land management with regards to pastoral production (Donald *et* al, 1996;Wilkinson, 1999; McIvor *et al*, 2011). High rainfall combined with steep slopes and unstable soils mean some form of protection is needed to control or reduce erosion events.

The purpose of this review is to recognise the need for space-planted conservation trees within New Zealand as a soil erosion control measure. Furthermore, the review is to identify contributing factors that determine pasture production below the canopy. Previous literature has predominately been based around agroforestry blocks and stands of young or mature deciduous trees. The objective is to determine what is impacting understory pasture production in trees that have been space-planted for soil erosion management of hill pastures.

Prior to European settlement approximately 170 years ago, 66 % of New Zealand's land surface was forested in predominately evergreen, coniferous and broadleaved vegetation, combined with scrublands (Blaschke *et al*, 1991; Wilkinson, 1999). However, from the 1840's through to early 1980's, rapid conversion to farmland for pastoral development took place over hill country land, due to the large proportion of international earnings which came from the meat and wool sector (Wilkinson, 1999), reinforced by social and political support (Dodd *et al*, 2008). As a result, subsequent years saw New Zealand encounter serious land degradation by erosion (Blaschke *et al*, 1991) which led to the development of government environmental legislation for the conservation of soil resources and flooding control, with an objective for promoting sustainable management of agricultural land. The current legislation governing sustainable management of agricultural land is the Resource Management Act, 1991 (Wilkinson, 1999).

The vulnerability of New Zealand's landscape became apparent when substantial environmental issues such as a decrease in soil productivity, water holding capacity and accelerated slope erosion, together with problems such as declining water quality levels, increased water runoff and loss of biodiversity were identified across the country (Blaschke *et al*, 1992; Wilkinson, 1999; McIvor *et al*, 2011). Previous studies have found that there is a direct correlation between European settlement, sedimentation levels and deforestation rates, with deforestation resulting in an approximate 10-fold increase for long and short-term erosion (Page *et al*, 1994b; McIvor *et al*, 2011). Blaschke *et al*, (1992) examined ecosystem process changes that occur as a result of deforestation and erosion events in New Zealand. Trustrum *et al* (1990) showed that on pastoral slopes >42°, soil loss exceeds soil formation (hence unsustainable pastoral farming on steep country), and on slopes 28-42° he suggested that soil loss limits pasture growth and still contributes to sediment loading. Findings from their study showed that hill slope depths varied significantly with soil profiles in the 28°- 42° slope class, with a net erosion depletion rate over 75 years of at least 2 mm $year^{-1}$. Furthermore, with 69 % of the country having slopes greater than 12°, being classified as hill country, there is an urgency to protect a major income earner for the New Zealand economy (McIvor *et al*, 2011).

2.1 Use of Poplar Trees

One of the most successful hill country erosion control practices has been the establishment of space planted willow (*Salix*) and poplar (*Populus*) as soil conservation trees (Donald *et al*, 1996; Wilkinson, 1999; Guevara-Escobar *et al*, 1998; McIvor *et al*, 2011). They are among the fastest growing conservation trees, with rapid initial growth rates of both above and below ground material, all the while improving soil strength due to mechanical reinforcement from their root systems (Ekanayake *et* al, 1997; Wilkinson, 1999; McIvor *et al*, 2009). Previous research on the root contribution to soil strength showed that it varied depending on the strength and morphology of the roots coupled with the physical and chemical composition of the soil (Ekanayake *et al*, 1997). Research has shown that soils containing roots in comparison to fallow soils have the ability to undergo significantly more shear displacement before failure and landmass movement occurs (Ekanayake *et al*, 1997). An investigation completed at 278 sites around New Zealand showed that various poplar and willow species together controlled 63% of earthflows and prevented gully erosion at a staggering 42% of the sites (Thompson & Luckman, 1993). Douglas *et al* (2011) reported a 95 % reduction of soil slippage due to space planted conservation trees on slopes between 25-30°.

Conservation poplars are effective in drying out and binding the soil through increasing evapotranspiration and increasing soil strength, as it is found that waterlogging is more frequent in an open-pasture situation, compared to tree understory (Guevara-Escobar *et al* 1997). Volumetric soil water in both tree understorey and open pasture system can be measured using the Time Domain Reflectometry (TDR) technique. Guevara-Escobar *et al* (1998) found that tree understory was overall drier at 0-300 mm depth. However, there is a knowledge gap related to soil moisture under space-planted poplar trees of varying ages, as previous research has been conducted under agroforestry blocks, or on comparisons between very young and matured poplar trees.

Poplars and willows can mitigate against forage shortage, as they have an average growth rate of 1m to 4m from poles coupled with a nutritive value similar to lucerne and are rich in selenium, copper, zinc, nitrogen and phosphorus macroelements (Wilkinson, 1999). Overall, conservation trees have the potential to add value and improve pastoral enterprises susceptible to erosion.

2.2 Root development in Poplar trees

Introduction of poplar trees following deforestation on erosion prone hill-country has had several benefits for livestock, with provision of shade and shelter and seasonal fodder (Wilkinson, 1999; Dodd *et al*, no date specified; National Poplar and Willow Users Group, 2007). Moreover, the ability of poplars to establish from unrooted poles (2.5-3m) and develop extensive root systems that successfully stabilise soil masses, on top of cheap production costs and minimum protection required, make them a leading choice for pastoral slope stabilisation (Wilkinson, 1999; McIvor *et al*, 2011). While it has been reported that there are minimal data available on root development of soil conservation trees grown under New Zealand conditions (McIvor *et al*, 2009), it has been shown for 'Veronese' poplar that there is a positive relationship between diameter at breast height (DBH) of the tree and root mass (McIvor *et al*, 2009). Results indicate that for the first 5 years, little root development occurs (total length of fine roots equals 79.4 m). However, once established this rapidly increases as shown in 7 year old (349.3 m) and 9.5 year old (1611.3 m) poplar trees (McIvor *et al*, 2009;2011). When planted correctly, between 5-10 years after planting, poplars are able to reduce soil erosion to a level where hillsides are considered stable (Wall *et al*, 2006).

2.3 Canopy Cover and Pasture Production

Animal production in hill country areas is predominately driven by pasture systems which are grazed year round, producing dry stock commodities such as meat and wool for export (Dodd *et al*, 2008). A pasture grazing system is seasonally variable due to climatic variations but also changing fertiliser inputs and dung and urine deposition from animals for soil nutrients (Guevara-Escobar, 1999). One of the negative effects of integrating space planted trees into a grazing system, is a reduction in pasture production caused primarily through light interception by the tree canopy. Stock congregating beneath space planted trees may concentrate urine and dung deposition in comparison to an open pasture situation where deposition is likely to be dispersed more evenly through the paddock. This also could contribute to a reduction in pasture production.

An annual reduction in understorey pasture growth of between 20 to 40 % in comparison to an open pasture situation has been reported (Gilchrist *et* al, 1993; Guevara-Escobar, 1999; Wall *et al*, 2006). McIvor & Douglas (2012) found that pruning to 6m of 8 year old Veronese poplars, planted at 8m spacing , on a hillslope increased light infiltration to the understorey from 66% to 77%. Wall *et al*, (2006) found that under 25, 50 and 75 % poplar canopy closure, annual pasture DM production was around 77, 60 and 48% that of an open pasture.

A study in Gisborne on Italian black hybrid poplar clones showed a 2% yearly reduction in pasture production at a planting density of 100 stems per hectare (sph), and a total of 24 % decrease within 8 years when canopy closure occurs (McElwee *et al*, 2000). Devkota *et al* (2001) found a 65 % reduction in net herbage accumulation directly beneath alder trees in comparison to unshaded pastures, with a minimum of 86 % canopy closure. Similarly Guevara-Escobar *et al* (1997) found annual pasture production beneath poplar trees was 60-70% of that in an open environment, and was of a lower feed value. In addition Guevara-Escobar *et al* (1997) reported that in a mature uneven-spacing poplar block, pasture beneath the trees was also of a lower feed value.

One of the major limitations of past literature surrounding poplars and annual pasture production however, has been a lack of information on the age of the poplar trees combined with the type of system they were in. A large proportion of research has been completed under agroforestry blocks, poplar tree 8 years and younger or mature poplar stands, when looking at the impact they have on understorey pasture production. While in some situations, the decrease in pasture production is quite substantial, once slippage or soil erosion has occurred on a pastoral slope, annual pasture production can take up to 80 years to recover, only ever recovering to 80 % of original production (Hicks *et* al, 2000; Wall *et al*, 2006; Rosser & Ross, 2011; McIvor & Douglas, 2012). Studies in the Wairarapa, Wairoa and Taranaki hill country have shown that landslip recovery from erosion events takes between 20-40 years to recover back to 70-80% of previous pasture production levels (DeRose *et* al, 1995; Wall *et al*, 2006, Rosser & Ross, 2011).

3.0 Materials and methods

3.1 Field site description

Two pastoral hill sites were selected with similar slope angle, aspect and climatic conditions, each with space-planted *Populous deltoids x nigra* 'Veronese' poplars at similar spacing but differing in tree age. The chosen sites were also comparable with regard to stock management grazing systems and fertiliser history. Both study sites were located in Rongomai, near Eketahuna on the Lower East Coast of the North Island, New Zealand.

Study site A is situated on a Mahoenui Silt Loam Soil, with moderately good drainage (Fig. 1). The site is positioned on a western aspect with an average slope of 22.4 degrees. The poplars are space-planted approximately 10m apart in a grid formation. The poplars were estimated to be 8-10 years old with a diameter at breast height (DBH) in the range of 26-31 cm.

Site B is located approximately 2 kilometres south of site one, on a Purimu Silt Loam, which is an imperfectly draining soil (Fig. 2). The trees are situated on a western aspect with an average slope of 23.5 degrees. The trees were space planted 11 metres apart in a grid formation. The poplars are estimated to be 17-19 years old with a DBH in the range of 51-54 cm.

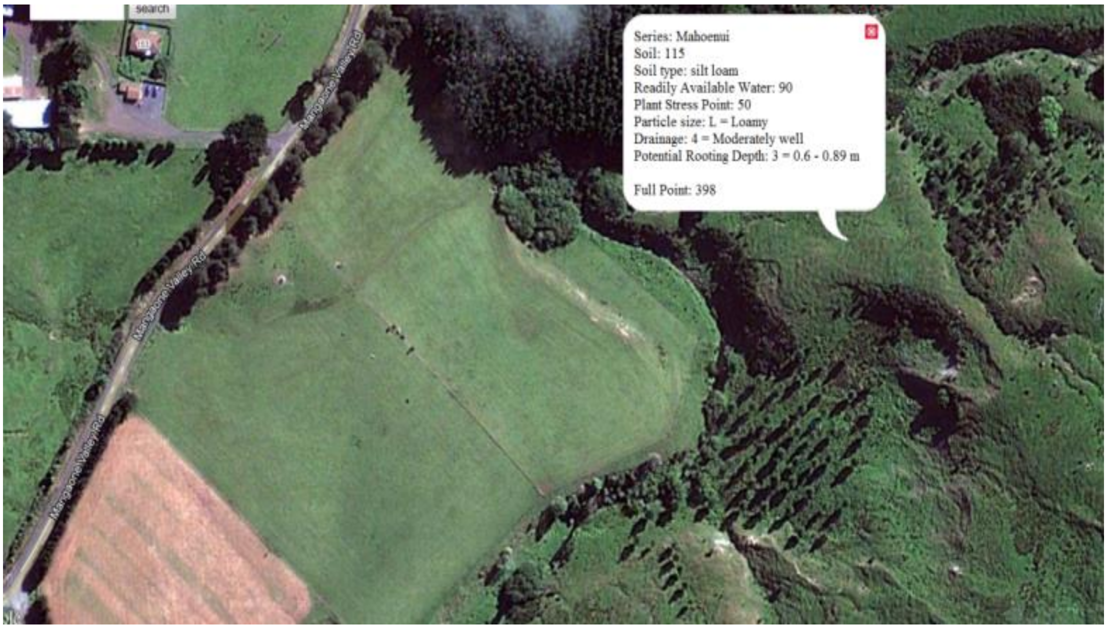

Figure 1: Location of site A, the young experimental unit. Soil data were obtained from Landcare Research's Fundamental Soil Layers Database, using the CropIRLog software (HortPlus NZ Ltd). The soil hydraulic properties shown in this figure are defined in Appendix 2 and they are important inputs for modelling the site water balance.

Figure 2: Location of site B, the mature experimental unit. Soil data obtained from Landcare Research's Fundamental Soil Layers Database, using the CropIRLog software (HortPlus NZ Ltd). The soil hydraulic properties shown in this figure are defined in Appendix 2 and they are important inputs for modelling the site water balance.

At each location, the equipment used for the experiment was installed within a single square area defined by a tree at each corner (referred to subsequently as an experimental unit (EU). and we chose a control site in the open which was situated well away from any shadowing effect of the trees. The four neighbouring trees were buffered by poplars of the same age to eliminate as far as possible bias due to border or edge effects. Throughout the experimental period, sheep and cattle grazed the study sites according to the farmer's normal grazing rotation pattern. No fertiliser had been applied to the paddocks which incorporated the study sites for a year prior to beginning data collection. Figure 3 shows the shadow pattern under the mature trees at Site B. Pasture cages were placed on the ground under the tree canopy, at 7 locations within each EU to exclude grazing events and to monitor net pasture production (Fig. 4).

Figure 3: The mature trees at field site B illustrating the shadow area on the ground and the type of farming system (hill country dry stock system) currently being employed.

3.2 Soil Sampling

Soil sampling was carried out within each experimental unit to investigate the impact of the trees on the nutrient balance and fertility of the soil. A 25 mm diameter soil corer was used to collect the samples, at 0-75 mm and 75-150 mm depths. Three sample sets were collected at randomly locations within the perimeter of each pasture cage. Soil samples were also taken in the open environment, once again sampled randomly under each pasture cage. Each soil sample was passed through a 2 mm sieve, with a subsample taken and stored at 4°C. The soil samples were later analysed for carbon, nitrogen by Elemental as well as soil pH in the soil laboratory of the Institute of Natural Resources, Massey University, Palmerston North.

3.3 Field Instrumentation

3.3.1 Pasture exclusion cages

Exclusion cages were used to measure pasture production at each site, both within the EU under the trees and out in the open site (Fig.3). The pasture cages under the EU were placed in zones located at specific distances from the tree, namely; close by the trunk, mid-canopy and in the centre of the four trees. Pasture samples were collected once every 60 days, using a quadrat ($0.0625m^2$) to randomly sample two areas within each of the pasture cages. This was carried out using the trimming technique developed by Radcliffe (1974) that uses grass shears with a sled attachment to cut the pasture to a height of 25 mm (Fig. 5). Each pasture sample was labelled, put into a brown paper bag and dried in an oven for five days at 60°C to remove any moisture. The total dried mass (DM) was then recorded and used to calculate the daily dry matter production (kg/ha/d), obtained from each quadrat.

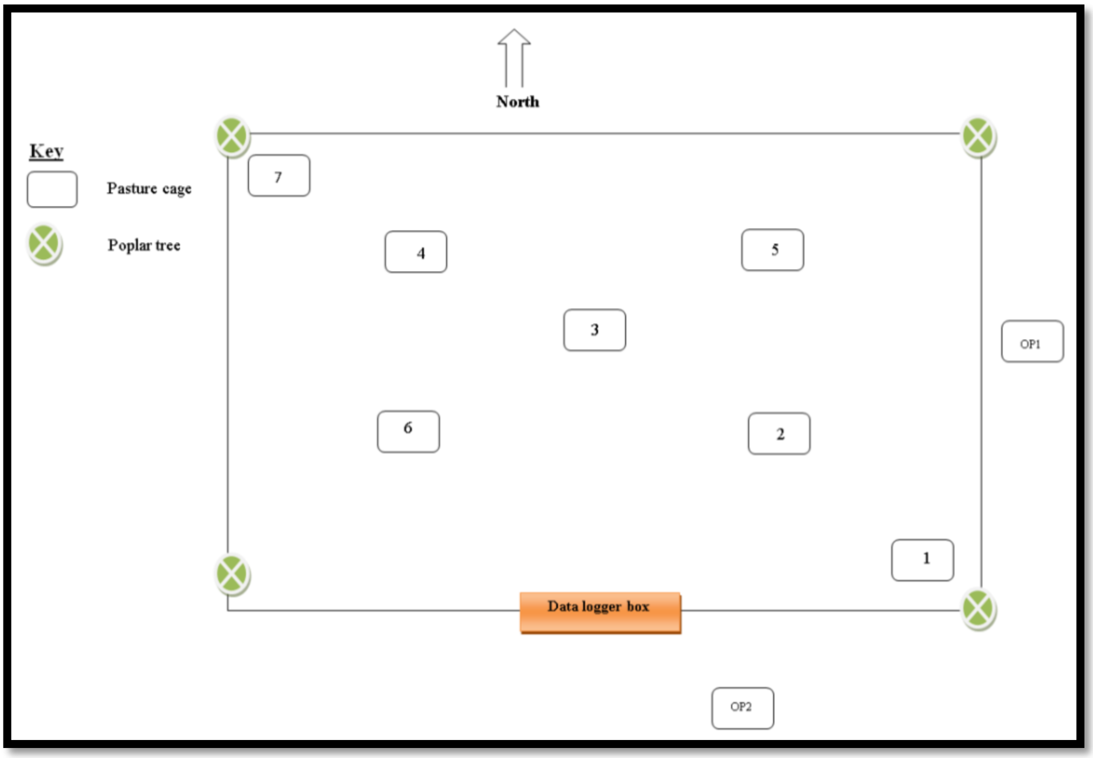

Figure 4: Pasture cage layout with the experimental unit for the mature study site.

Figure 5: Shearing shears with a sled attachment to sample the pasture in the exclusion cages to a height of 25mm.

3.3.2 The transmission of Photosynthetically active radiation

An array of Quantum Sensors (Tranzflo NZ Ltd, Palmerston North) were installed to measure the proportion of photosynthetically active radiation (PAR) transmitted through the tree canopy (Fig. 6). All light sensor were mounted on poles at a height of 30 cm above ground to minimise variation of PAR measurements. The poles were 15 cm into the ground to resist movement from stock grazing. All light sensors were placed on a self-levelling bracket, to maintain the top diffuser (the white part) level and avoid any shading from the brackets.

Figure 6: The light sensor used to measure the amount of photosynthetically active radiation (PAR light) being transmitted though the leaf canopy to the understory pasture.

Prior to installation, each light sensor was calibrated against a reference standard (Li-Cor model 1800 calibration rig) as shown in Figure 7. Each sensor was wired directly to a datalogger (model CR10X, Campbell Scientific, USA).

In the field we connected a total of 17 PAR sensors to each data logger (one at each site) using an AM25T multiplexer powered by a 12V battery and recharged using a 6W solar panel. PAR measurements were recorded every 15 seconds and an average of all the readings was then determined once per hour in standard time. This process allowed for synchronisation with other climate data that were obtained from NIWA's Virtual Climate Station Network (www.cliflo.niwa.co.nz). For the purpose of modelling, we downloaded a time series of daily climate data from the nearest NIWA site. For this experiment, data was obtained from Agent No 27241 (Latitude 40.625, Longitude 175.775). This database was used in the absence of a weather station at the study sites.

Figure 7: A reference standard light source (Li-Cor model 1800-01) was used to calibrate each of the quantum sensors prior to installation in the field experiment.

3.3.3 Soil Moisture: Time Domain Reflectometry technique

The time domain reflectometry (TDR) was used to monitor the soil's volumetric water content (0-30 cm deep) at each of the experimental sites. The TDR probes (Model CS616, Campbell Scientific, USA) were wired directly into a datalogger (Model CR10X, Campbell Scientific, USA) with one TDR assigned to each exclusion cage within the EU. Soil water contents were measured once every minute and an average of all the readings was determined once every hour in standard time.

Following an assessment of the TDR data values from both Site A and Site B were deemed to be suspect as the results indicated constant saturation across a majority of the months, consistent with a possible fault with the instrumentation or the analysis. So, modelling was needed to estimate the soil water balance over the experimental period. For this purpose, virtual climate data was also obtained from NIWA's Virtual Climate Station Network (www.cliflo.niwa.co.nz) to provide a time series of daily records dating back to 1972.

3.4 Modelling to determine non-measured factors influencing pasture production

3.4.1 Poplar daily water use

The daily water use of the poplars at each experimental site was calculated using a soil water balance model similar to CropIRLog (HortPlus NZ Ltd). A full description of the modelling framework is described in the supporting documentation which can be found on the web site (www.cropirlog.co.nz), so only the salient details are presented here. Firstly, a reference evaporation rate ET_o [mm d^{-1}] was calculated using the FAO-56 Penman-Monteith model given by:

$$ET_0 = \frac{\frac{s}{\lambda}(R_N - G) + \gamma \frac{900}{(T+273)} u_2 (e_S - e_a)}{s + \gamma\,(1 + 0.34 u_2)}$$

Eq. [1]

R_N [MJ m^{-2} d^{-1}] = net solar radiation

G [MJ m^{-2} d^{-1}] = ground heat flux

T [°C] = mean air temperature

e_S [kPa] = mean actual vapour pressure of the air

u_2 [m s^{-1}] = mean wind speed

s [Pa °C^{-1}] = the slope of the saturation vapour-pressure versus temperature curve

y [66.1 Pa] = the psychometric constant

ƛ [2.45 MJ kg^{-1}] = latent heat of vaporisation for water

This equation determines the potential rate of evaporation from a green grass cover surface that is actively growing with a short, uniform height which is completely shading the ground and isn't short of water (Allen *et al.*, 1998). The corresponding evaporation rate of the stand of poplar trees is calculated as:

$$ET_c = K_s.K_c ET_o \qquad \text{Eq. [2]}$$

where K_c is a dimensionless 'crop factor' that relates stand evaporation rate to the atmospheric demand set by ET_O. This crop factor can vary anywhere from 0.1 for a young plant with a small proportion of leaf area up to 1.2 for vigorous plants with a large leaf area index (area of leaf per unit area of ground). In this case the K_C value for the spaced trees was estimated to be 0.4 at Site A (young trees) and 0.7 at Site B (mature trees), based on the procedure outlined in the FAO-66 guidelines for crop water use (Steduto et al 2012). Evapotranspiration is significantly affected by the leaf area development of the tree canopy, the fraction of ground cover, the tree height and the stomatal control of transpiration (Allen *et* al, 1998), amongst other factors. For the purpose of modelling, we also use another factor, K_S, to describe the impact of water-stress. An over view of the soil water balance is provided in Appendix 2.

3.4.2 Soil water status

Typical values for the soil's hydraulic properties at the two research sites have been used to define the soil water holding capacity and drainage characteristics of each site (Figs 1 & 2). The soil water availability is needed for the modelling to determine the overall soil water status during the experimental period. The soil water content was calculated using a daily soil water balance model that considers 'inputs' of water from rainfall and 'losses' of water from evapotranspiration, rainfall interception, run-off and drainage (see Appendix 2 for details). Model outputs of soil water content, averaged over a root-zone depth of 50 cm, are used to determine a stress-response function, f_W, that also reduces pasture production, as described below.

3.4.3 Runoff of rainfall Each site has a slope of more than 20 degrees so that the runoff of rainfall is likely to be an important component of the site water balance. We have no measurements of runoff from the sites. Instead, surface runoff of rainfall is calculated from the daily rainfall total which was deduced from the NIWA Virtual Climate database (www.cliflo.niwa.co.nz). The runoff calculation uses the Soil Conservation Service (SCS) curve number approach for runoff and the Revised Universal Soil Loss Equation (RUSLE) for sediment transport (Williams 1991). This component of the water balance was then incorporated into the overall model, and includes modifications that account for slope and drainage class. The soil at Site A is moderately well-drained while the soil at Site B is poorly drained, and so we expect less and more runoff, respectively, for the same amount of rainfall.

3.4.4. Crop Growth

Daily biomass production of the grass is modelled using a potential production rate per unit ground area, G (kg m^{-2} d^{-1}) that is related, via a conversion efficiency, ε (kg MJ^{-1}), to the amount of solar radiant energy, Φ_G (MJ m^{-2} d^{-1}), reaching the understory:

$$G = \varepsilon \Phi_G \; f_T \; f_N \; f_W \qquad \text{[Eq. 3]}$$

Here f_T, f_N and f_W are response functions that range between zero and unity depending on temperature, plant nitrogen and soil water status respectively (Eckersten & Jansson 1991). In a complete model the values of Φ_G would be predicted from incoming daily global radiation, stand dimensions and the canopy leaf area index (e.g. Green et al., 2003), but this was outside the scope of the current project. Instead, a simple empirical function was used to describe the seasonal pattern of Φ_G based on the light sensor data (Figs 11 & 12). Furthermore, we have no data to represent the nutrient response function, f_N, and so this factor was assigned a value of one. Finally, the value of ε was 'tuned' to match the data from the pasture cages. The empirical approach also then accounts for other unknown effects such as stock damage, due to grazing and treading, as well as historical damage that may have occurred due to previous erosion events.

Modelled values of G then depend on the daily sunshine and temperature, and are moderated by the soil's water status (King 1993). A fraction of the daily growth is allocated to above and below ground biomass (i.e. the leaves and the roots of the grass), with senescence rates being moderated by abiotic functions of soil temperature and moisture status (Thornley et al. 1995). Pasture growth is maximised only if soil water and soil nutrients are non-limiting, and the trees cast minimal shade. In our case, comparing pasture growth under a young vs mature stand of poplar trees, we recorded a 65-90% reduction in the light level on the ground. Therefore, the trees are expected to have a significant impact on understory pasture production. Grazing events were modelled in the following manner: as soon as the pasture dry-matter exceeded 2500 kg/ha, it was reduced back to 1000 kg/ha. This results in 5-7 grazing events each year, which seemed to be reasonable.

3.5 Statistical analysis

Pasture dry matter from the two or three quadrats taken from each cage were averaged before further analysis on each sample date. Because the same cages were repeatedly sampled, a linear mixed model was fitted with a correlation model to take into account the repeated measures. The factors analysed were the site, the cage position, and the sample month. Comparisons among means were made using 5% LSD (least significant difference) values.

4.0 Results

4.1 Pasture exclusion cages

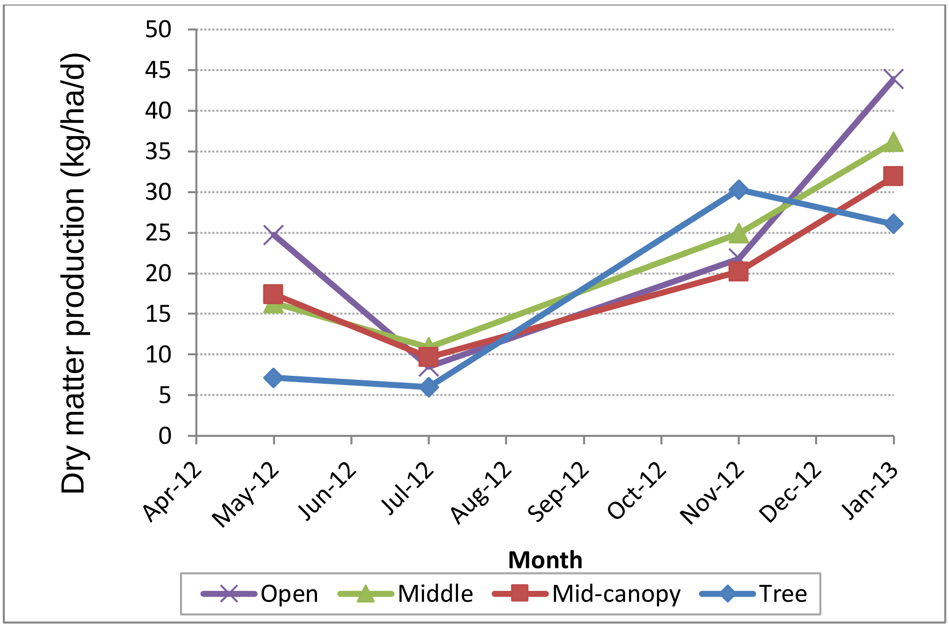

Figure 8: Mean dry matter production (kg/ha/d) over time for the four cage positions at Site A.

Figure 8 shows the DM production recorded from each pasture cage location at site A. Similar data for Site B are shown in Figure 9. DM production tended to be higher at site A compared with site B. The seasonal patterns of DM production were similar at both sited (cf. Figs 8 & 9), with peak dry matter production in summer being 44 kg/ha/d under the young trees and just 21% under the polder trees, presumably dues to the increased shading effects. In July, when the trees had no leaves, differences in pasture production among the cage positions, ranged from 6-12 kg/ha/d, though the differences were not significant. Pasture production mid-winetr at Site A was similar to that recorded at site B. However, DM production under the trees was much closer to that measured for the open site at site A than at site B. For example, mean summer DM production under the young trees was 70-80% of that in the open, whereas for the older trees, this value was around 35%.

Differences in DM production as influenced by the age of the trees at the different cage positions and averaged across all seasons are shown in Figure 11. As a percentage of DM production in January (the peak DM production sample time) in the open, production in middle, mid-canopy and tree locations for site A are 82%, 73% and 59%; and for site B are 33%, 33% and 43%, respectively.

Moreover, pasture growth for the summer period was 41% higher in the open pasture when compared to pasture production at the tree, however, the greatest change from winter to spring in pasture growth occurred at the tree (80% increase) with a 64% increase in pasture production in the open pasture.

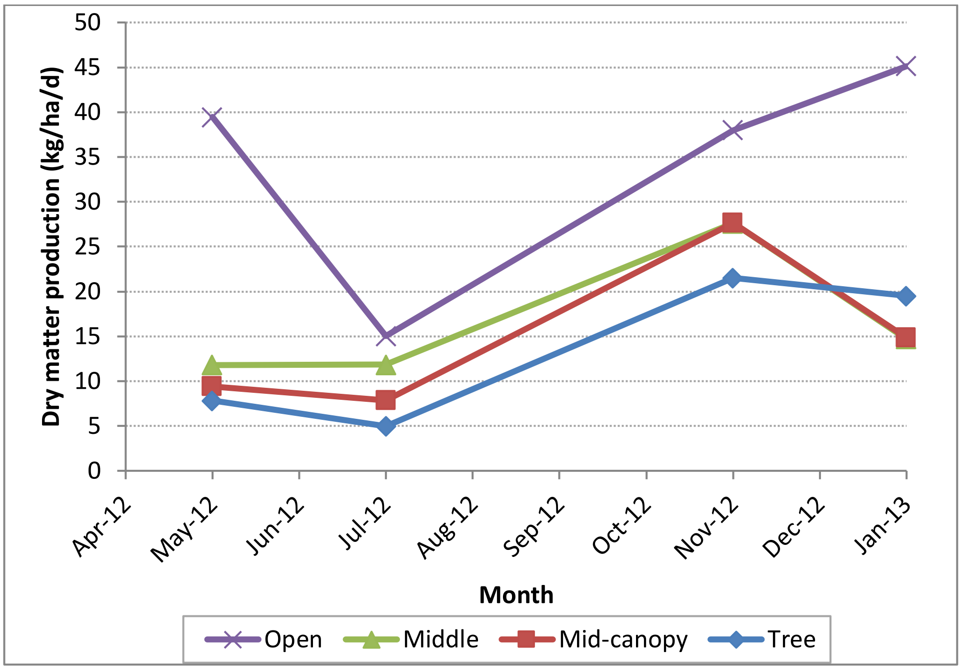

Figure 9: Mean dry matter production (kg/ha/d) over time for four cage positions at site B.

DM production varied at each of the pasture cage locations within the EU for site B. As expected, DM production was greatest for the open pasture cage and least for those cages closest to the base of the tree, where a 66% reduction was recorded. DM production in the centre and mid-canopy locations of the EU were greater than close to the tree but much lower than production of the open site. Overall, there was a 50% reduction in DM production within the trees from Spring to Summer.

Site A (the young site) showed a steady increase pasture production from July through November to January, whereas production at site B increased from July to November and then decreased in January (Figs 8 & 9). January was very dry with less that 25% of the normal (average) rainfall being recorded.

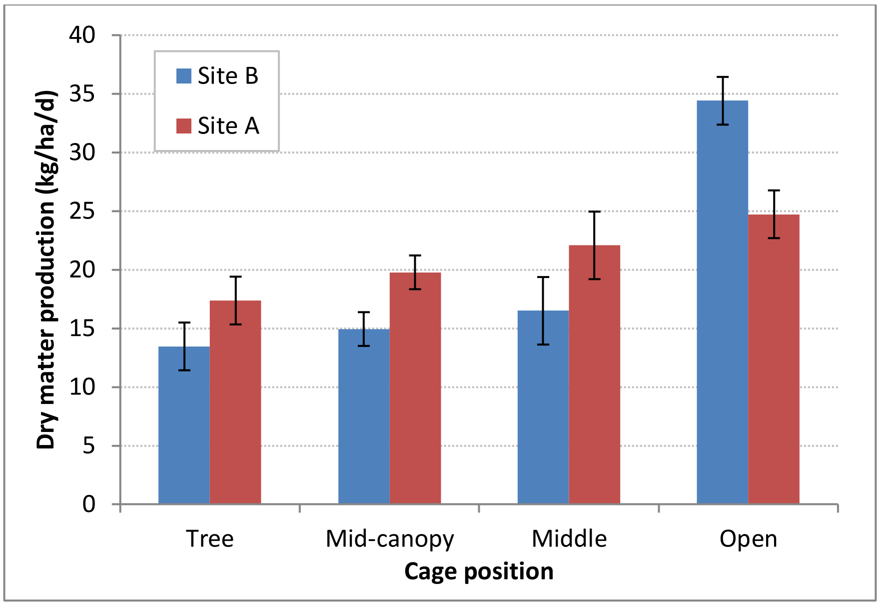

Figure 10: Mean dry matter production (kg/ha/d) at the two sites and four cage positions, averaged over all months. Error bars represent one standard error of the mean.

Figure 10 demonstrates a steady decline of pasture production closer to the base of the tree compared with corresponding data from the open pasture cage at site A. Averaged over all months, total pasture production of the tree, mid-canopy and middle cage positions in comparison to the open pasture was 70%, 80% and 89 % respectively. Meanwhile, at Site B, total pasture production of the tree, mid-canopy and middle cage positions in comparison to the open pasture was much lower, being 39%, 43% and 48% of that recorded at the open site

Table 1 below gives a breakdown of mean dry matter production across the four cage positions of both site A and B for the four sample times. There was greatest variance at the middle cage position while the mid-canopy cages showed the least variance.

Table 1: Mean dry matter production (kg/ha/d) of the understory pasture at the two sites, for four different cage positions and four sample times. SEM represents one standard error of the mean. Site B has mature trees and Site A has young trees.

		Position			
Site	Month	Tree	Mid-canopy	Middle	Open
Site B	May-12	7.8	9.4	11.8	39.5
	Jul-12	5.0	7.9	11.8	15.0
	Nov-12	21.5	27.6	27.6	38.0
	Jan-13	19.5	14.8	14.7	45.1
Site A	May-12	7.1	17.4	16.3	24.7
	Jul-12	6.0	9.7	10.9	8.5
	Nov-12	30.3	20.2	24.9	21.8
	Jan-13	26.0	31.9	36.2	43.9
SEM		4.1	2.9	5.8	4.1

There was a significant seasonal difference in mean dry matter production in the different months (P<0.001, Table 2), between cage positions (P<0.001) and between month x site (p= 0.001) and month x position (P=0.006). Differences in mean dry matter production between sites were not significant (p = 0.28) though notably Site A had significantly greater production than the Site B in January 2013 (Table 3). We speculate that this could be the result of a combination of increased water stress on the pasture, due to greater tree transpiration, and increased shading from the larger canopy of the more mature trees.

Table 2: Values for linear mixed model F-tests for significance of factors affecting dry matter production.

Term	P-value
Month	<0.001
Site	0.28
Position	<0.001
Month×Site	0.001
Month×Position	0.006
Site×Position	0.001
Month×Site×Position	0.27

Table 3: Mean dry matter production (kg/ha/d) averaged over all cage positions for two sites and four sample months. Means with the same letter are not significantly different (5% LSD comparison). SEM = standard error of the mean.

	Site	
Month	Site B	Site A
May-12	17.1b	16.4b
Jul-12	9.9a	8.8a
Nov-12	28.7cd	24.3c
Jan-13	23.5c	34.5d
SEM	2.2	2.2

4.2 PAR light transmission

Daily PAR values from each light sensor were averaged to represent the light transmission for each pasture cages. The results were then modelled using a line of best fit to identify the seasonal pattern of the percentage light transmission at different positions within the EU, and an average was calculated across all sensors for each site. For example, Figure 11 shows the average light transmission on the ground at Site B in comparison with the open situation. When the trees were in 'full leaf' the light transmission was measured to be only about 13% of the open site. The loss of leaves from the tree during late autumn resulted in light transmission increasing from 13 % to 30 %. Even with no leaves present (mid-winter) the light transmission under the mature stand of trees was still only about 30% of the open site. Light transmission on the ground beneath the younger trees, at Site A, ranged between about 20% at full leaf-canopy to about 36% after leaf fall. Thus, the trees has a significant impact on light levels reaching the pasture.

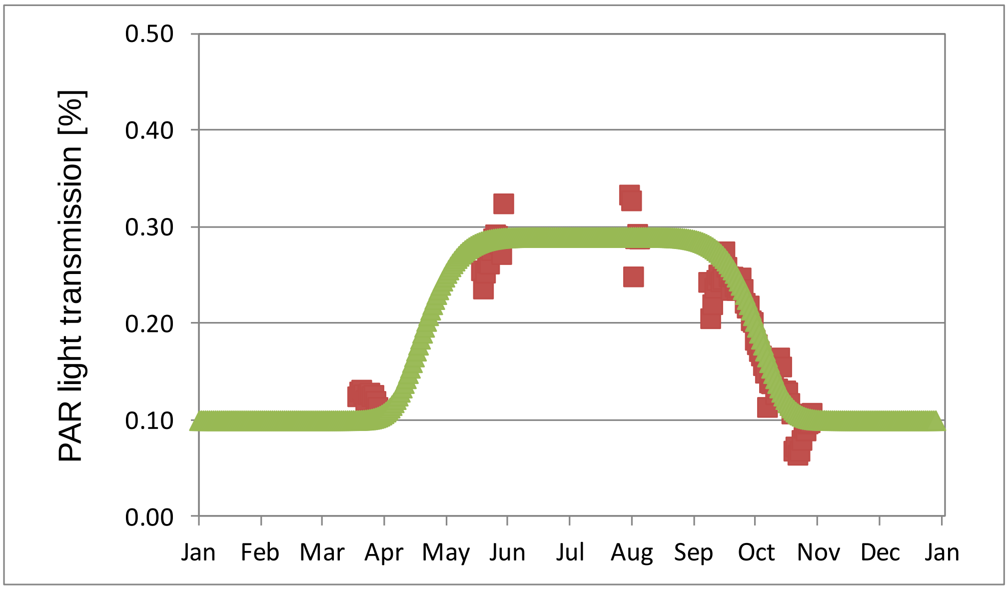

Figure 11: The average light transmission measured by an array of 7 PAR light sensors placed on the ground under the mature poplar trees at Site B (markers). The line represents a simple empirical function fitted to the data point to describe the light level on the ground, Φ_G, that is used to model pasture production via Eq. 3.

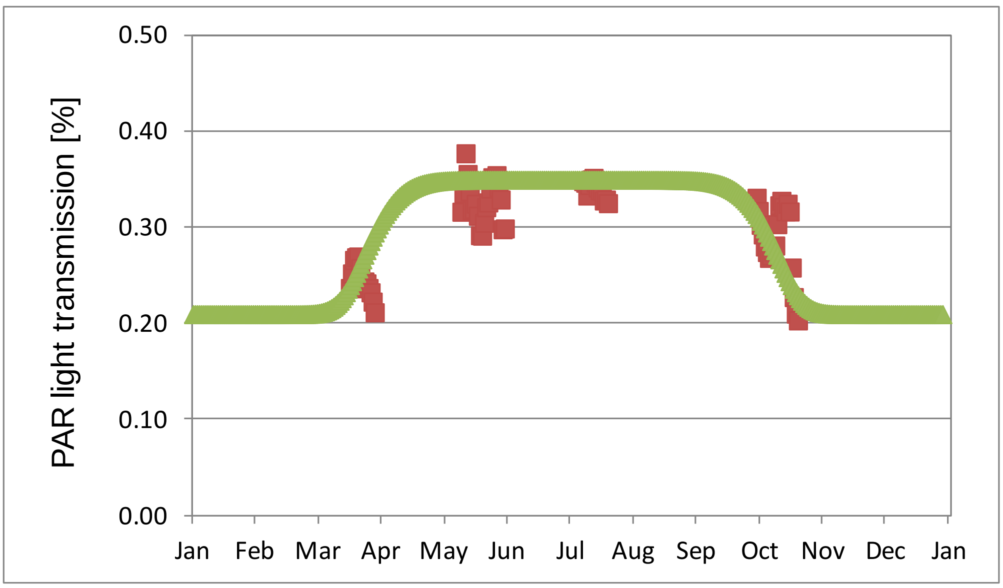

Figure 12: : The average light transmission measured by an aray of 7 PAR light sensors placed on the ground under the young poplar trees at Site A (markers). The line represents a simple empirical function fitted to the data point to describe the light levels on the ground, Φ_G, that is used to model pasture production via Eq. 3.

4.3. Modelling the impact of the trees on net pasture production.

Figures 13 & 14 show model outputs for the net pasture production under the trees at the two EU's, based on measured light transmission and the modelled soil water content. It can be seen that actual pasture production in mid-summer (Jan) is significantly lower in comparison to what the model has predicted. Reasoning behind this is due to the very dry periods experienced throughout New Zealand, where drought stress conditions have considerably compromised grass growth. Remaining variables such as nutrient stress and cattle treading damage may have also impacted on pasture production. These factors have not been incorporated into the model.

Overall, annual pasture production at Site A was estimated to be 7400 kgDM/ha with production at Site B 5700 kgDM/ha. Site A (younger poplars) pasture production was calculated to be greater based on the parameters used in the model and the actual data collected within this experiment (figs 13 and 14).

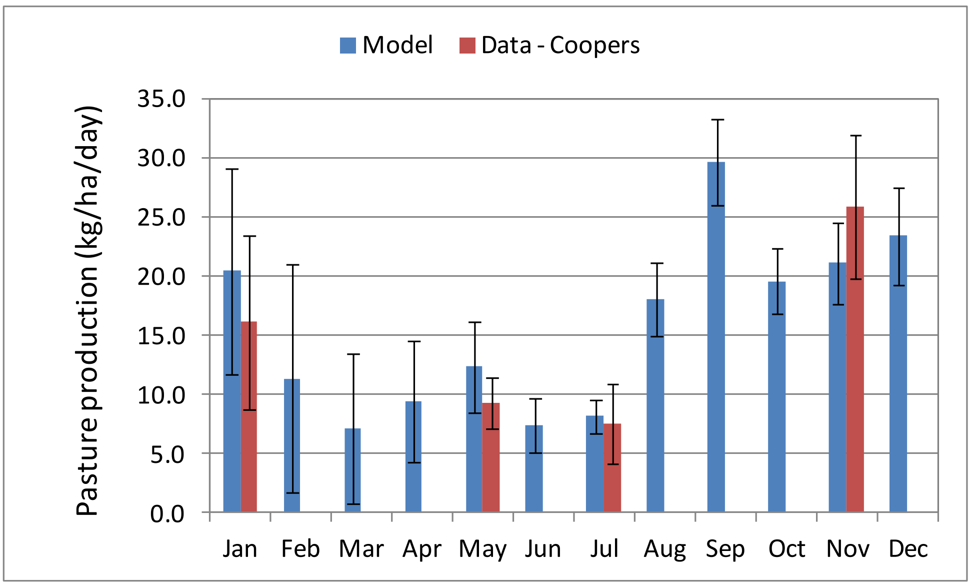

Figure 13 Modelled pasture production over 12 months for site B based on data of pasture production measured for the exclusion cages and long term climate data (Jan 2000-Jan 2013). Calculate annual pasture production of 5700 kg/ha.

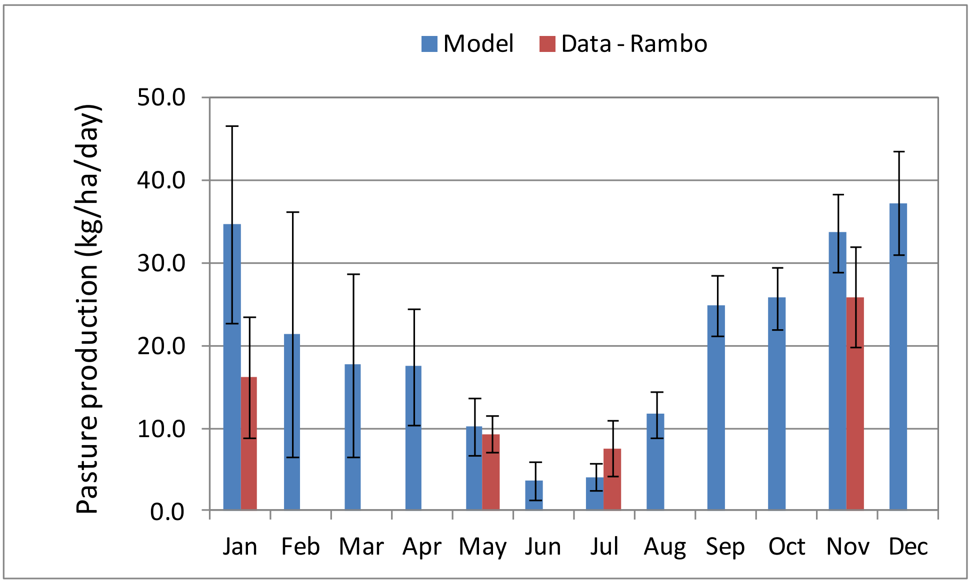

Figure 14 Modelled pasture production over 12 months for site A (young trees) based on data of pasture production measured for the exclusion cages and long term climate data (Jan 2000-Jan 2013). Calculate annual pasture production of 7400 kg/ha.

4.4 Soil analysis

Tables 4 & 5 identify soil trend data with regards to carbon, nitrogen and pH levels with the soil at each of the experimental units, for the top 15 cm of soil depth. In the top 7.5 cm of soil, we see that soil carbon and nitrogen levels are progressively higher as you increase the distance from the tree. However, the results do not portray a trend with regards to carbon and nitrogen levels at the 7.5-15 cm depth. At the same time, pH levels are significantly higher within the EU when compared to the open situation (pH = 5.9), with a maximum pH of 6.8, Premumably this is due to the greater deposition of urine from animals that camp under the trees.

Table 4: Nitrogen, carbon and pH soil analysis completed at two depths for the various cage positions across the young EU.

Site A	*Average 0-7.5cm depth*			*Average 7.5-15cm depth*		
	N	C	pH	N	C	pH
Tree	0.39	3.85	6.6	0.265	2.25	6.65
Mid-Canopy	0.36	3.475	6.75	0.29	2.475	6.75
Middle	0.4	3.9	6.8	0.27	2.2	6.7
Open	0.42	4.05	5.9	0.295	2.6	5.95

Table 5 results show similar outcomes to Site A. Soil carbon and nitrogen levels increase with distance from the tree. It can be seen that nitrogen and carbon levels are higher in both EU's at the base of the tree compared to the mid-canopy section. At the same time, pH levels are fairly constant within the EU but tend to be higher than the pH level in the open pasture site.

Table 5: Nitrogen, carbon and pH soil analysis completed at two depths for the various cage positions across the mature EU.

Site B	*Average 0-7.5cm depth*			*Average 7.5-15cm depth*		
	N	C	pH	N	C	pH
Tree	0.47	4.7	6.2	0.30	2.6	6.1
Mid-Canopy	0.46	4.4	6.2	0.26	2.2	6.2
Middle	0.52	4.8	6.2	0.28	2.3	6.2
Open	0.65	6.4	5.9	0.35	3.4	5.5

5.0 Discussion

5.1 Difference in pasture production at different locations under the trees

This study suggests that pasture production rates vary in relation to distance from the base of the tree within a space-planted tree environment. In this research project, pasture production was greatest in the middle location (middle) and had the lowest pasture production levels at the base of the tree (tree), as shown in Figure 10. The pattern of pasture production was consistent across all seasons, with greates growth rates in the spring and lowest growth rates in the winter. Comparison between light transmission and pasture growth had a positive relationship, with pasture growth diminishing as the proportion of transmitted light decreased closer to the tree.

5.2 Difference in pasture production compared with the open

Pasture production under the trees was significantly lower than in the open, with pasture growth being only 89% (Site A) and 48% (Site B) that of the control site. This is consistent with previous research conducted under poplar stands and mature trees greater than 25 years (Gilchrist *et al.,* 1993; Guevara-Escobar *et al.*, 1998; 1999) indicating a diminishing effect closer toward the crown of the tree.

Pasture production in an open situation is not limited by light when compared to a space-planted situation. Leaf area index, light transmission and reduced soil moisture levels are all the key factors contributing to a reduction in understorey pasture growth. This is demonstrated in Figs 11 and 12 where leaf fall has led to an increase in light transmission from 20% (Site A) and 13% (Site B) at full leaf canopy to 36% (Site A) and 30% (Site B) following leaf fall.

Soil moisture levels will play an important role in moderating pasture production. Figure 12 illustrates very low pasture production in mid-summer (January) that is associated with very low soil moisture levels due to the drought conditions experienced over the 2012-2013 growing season (one of the worst droughts in the past 50 or so years). The low rainfall (less than 25% of average) resulted in pasture production levels being about 45 % of the average pasture production as determined via the modelling (2000-2013). Conservation trees such as the poplar are effective in drying out and binding the soil through increasing evapotranspiration and soil strength.

During some site visits, we observed waterlogging to be more frequent in an open-pasture site compared to tree understory. Similar results were reported by Guevara-Escobar *et al* (1997). During the winter months, pugging damage at Site A (Figure 13) was very apparent which could also partly explain the reduction in pasture growth and similar growth levels to the mature EU. Loss of pasture growth due to physical damage to the plant causing death to the sward coupled with soil compaction increasing anaerobic conditions are the key contributors towards growth reduction (Johnson *et al.*, 1993). As a result, it is suggested that pugging damage at Site A may also have had an on-going influence on pasture growth. The soil moisture model includes the extraction of water from the trees and the grassed understorey. However, it does not accommodate changes in drainage characteristics such as pugging damage from grazing livestock.

Figure 13: Pugging damage from cattle over the winter months at Site A, leading to a change in preferential flows for surface water, compaction of topsoil and overall reduction in pasture growth.

5.3 Difference in pasture production with experimental units of various ages

Tree age is a major limiting factor surrounding pasture production, as the proportion of woody material and leaf material increases with tree age, up to 4m annually when grown from a pole (Wilkinson, 1999), leading to an increase in shade as the trees reach canopy closure. The model used here predicts an annual pasture production rate of 7400 kgDM/ha in Site A (young trees) and 5700 kgDM/ha in Site B (older trees). On average with the same poplar clone and planting-distances in the EU, we calculate an annual decrease of abpout 140 kgDM/ha/yr in understory pasture production.

5.4 Leaf material influence on pasture production

Suppression of pasture production could also be due to a contribution of leaf dry matter accumulation on the understory floor. It should be acknowledged that leaves which had fallen off the tree and then became wet due to a rainfall event, became lodged within the EU, thus inhibiting pasture production. It can also be seen the direct correlation between tree age and leaf material.

Light transmission through the poplar canopy is seen to significantly decrease from approximately September to November (Figs 11 & 12). As the year progresses from Winter to Spring, soil temperatures and evaporative demand both increase, drying out the soil and stimulating pasture growth. This is often offset by poplar bud break in Spring and a rapid increase in leaf canopy development. Furthermore, the leaf area index of poplar trees is expected to double between December and Febraury as branching occurs, carrying new shoots that eventually bud into leaves, therefore increasing light interception. Research conducted by McIvor & Douglas (2012) found that pruning to 6m of 8 year old Veronese poplars, planted at 8m spacing, on a hillslope increased light transmission to the understory from 66% to 77%.

6.0 Conclusions and Research Gaps

The results of this study suggest that space-planted Veronese poplars of different ages have a direct impact on understory pasture production. Soil pH levels were higher within the experimental unit in comparison to the open pasture but decreased with age. Impacts on soil carbon and soil nitrogen levels were less significant, although increased levels were noted from the base of the tree to the mid-canopy section over the top 150 cm of the soil profile.

Canopy closure and development was the key influencing parameter on understory pasture growth. The results showed that the leaf fall and bud break had an immediate impact on light transmission through the canopy which led on to pasture production levels. Growth rates decreased with tree age as woody material percentage and percent canopy closure increased.

The model successfully predicted the seasonal pattern of pasture production under both EU's. With a larger time frame, more refined models could be used to incorporate the effects of different tree spacings and leaf area densities (Green et al, 2003). Such models would would enable us to determine the impact of tree density on pasture production. It would also be beneficial to investigate in-depth the influence that slope and aspect has on understory pasture production in a space-planted setting. Furthermore, it would be beneficial to investigate the impact removing alternative space planted poplars on both subsequent root development and pasture production.

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7.0 Appendix

7.1 Definitions of soil hydraulic properties

The following definitions of soil hydraulic properties have been adopted for the modelling:

- Soil-water content (*SWC*, mm) is a measure of the soil's volumetric water content ($\bar{\theta}$, %), integrated (summed) over a specified depth, being a 1.0 m root zone (Δz, mm): $SWC = \bar{\theta} \Delta z$.
- Saturation (*SAT*, mm) represents the porosity of the soil spores (*POR*, %) multiplied by soil depth (Δz, mm). Poorly drained soils that are waterlogged are expected to be close to the *SAT* value during the winter.
- Full point (*FP*, mm) = field capacity (*FC*, %) multiplied by soil depth (Δz, mm). *FC* is a measure of the soil's volumetric water content at a matric potential of -10 kPa, averaged over a specified depth, being a 1.0 m root zone. The *FP* value represents the total depth of water held in the root zone soil that has recently been fully wet, by either rainfall and/or irrigation, such that all drainage has now materially ceased. The maximum *SWC* of free-draining soils is expected to be close to *FP* during the winter.
- Soil water deficit (*SWD*, mm) represents the difference between the full point and today's soil water content.
- Zero point (*ZP*, mm) = permanent wilting point (*WP*, %) multiplied by soil depth (Δz, mm). *ZP* is a measure of the soil's volumetric water content at a matric potential of -1500 kPa, averaged over a specified depth, being a 1.0 m root zone. The *ZP* value represents the total depth of water held in the root zone soil such that all plant-available soil water has been extracted and the plants have died.
- Total available water (*TAW*, mm) = the amount of water held in the root zone soil, between field capacity and wilting point: $TAW = (FC\text{-}WP)\ \Delta z$
- Drought tolerance (D_{TOL}, %) is a plant-parameter that defines the fraction of *TAW* that can be extracted from the root zone soil before the symptoms of water stress begin to occur. This is a simple approximation and here we will assume $D_{TOL} = 0.5$, for both the pasture and the trees and vines, although different values may be more appropriate for other tree species e.g. 0.7 for olives (Allen et al. 1998).
- Readily available water (*RAW*, mm) represents the amount of water in the root zone soil that can be extracted by the crop before the symptoms of water stress occur. The values of *RAW* are calculated from the product of D_{TOL} multiplied by *TAW*.
- Refill-point (*RP*, mm) represents the *SWC* when irrigation will be applied. This variable is used to set up the irrigation strategy. In the tests that follow, we have assumed a value of *RP* that is half way between *FP* and *ZP*. In other words, we have set the value of D_{TOL} to equal 0.5 throughout the growing season.

CropIRLog has some flexibility to adjust the value of *RP* seasonally e.g. to mimic a deficit-irrigation strategy for kiwifruit and grapes where *RP* is adjusted upwards during flowering and downwards closer to harvest to improve aspects of fruit quality.

7.2 Procedure for calculating the soil water balance

The soil water balance of the root-zone soil is calculated using a simple tipping-bucket approach that considers the soil water content, *SWC*, averaged over a specified soil depth, being a 1.0 m deep root zone. The water balance is represented by a simple sum of the inputs of water, from rainfall (*RF*) and irrigation (IR_a), minus the outputs (losses) of water from evapotranspiration (ET_a), drainage (*DR*) and runoff (*RO*). Small interception losses are also accounted for, as some of the day's rainfall is intercepted by the leaf canopy and subsequently evaporated without reaching the ground (this is discussed later). All calculations are made using a daily time step, and all variables have the dimensions of mm unless stated otherwise.

The water balance calculation proceeds as follows. Firstly, we calculate a 'temporary' value for *SWC** as the sum of yesterday's *SWC* plus today's rainfall and irrigation, minus today's actual evapotranspiration, namely:

$$SWC^* = SWC + (RF + IR_a) - ET_a \qquad \text{Eq. [4]}$$

The value of *SWC** cannot exceed the full point, otherwise drainage and/or runoff will occur. We do not separate *DR* and *RO* in the tipping-bucket scheme. Rather, we calculate the excess amount of soil water, above the full point, and confine this to runoff and drainage losses, which are calculated as:

$$DR + RO = \max\,(SWC^* - FP, 0.0). \qquad \text{Eq. [5]}$$

Thus, the *SWC* at the end of each day is calculated as:

$$SWC = SWC^* - (DR + RO). \qquad \text{Eq. [6]}$$

This simple calculation procedure obeys mass balance and ensures the soil does not wet above field capacity. It will work best when soil water content is below field capacity, as would be expected for well-managed irrigation over a typical summer period. In reality, all soils will temporarily wet up above *FC*, often for a few days following a large rainfall event, especially during the winter period or when excessive amounts of irrigation are applied. However, most free-draining soils will also drain back to field capacity a few days later. Furthermore, run-off is also known to be strongly influenced by rainfall intensity, soil moisture conditions, and slope, amongst other factors. We have not explicitly modelled these factors with the simple tipping-bucket scheme adopted in CropIRLog. This is because the soil would normally be below field capacity during those times when we are looking to apply irrigation. The actual evapotranspiration transpiration, ET_a, is calculated from the sum of the transpiration losses from the crop (trees and vines only), T_a, and evaporative losses from the understorey (ground), E_G, that comprises a fractional area of grass and a remaining area of bare soil, namely:

$$ET_a = T_a + E_G \qquad \text{Eq. [7]}$$

The actual transpiration of the tree or vine crop (excluding evaporative losses from the understorey), T_a, is related to the potential evaporative demand, ET_O, using the following relationship (modified from Eq. 10 to include a stress factor, K_S), namely

$$T_a = K_S\, K_C\, ET_O \qquad \text{Eq. [8]}$$

where K_C is a seasonal crop-factor that accounts for changes in the green leaf-area, and K_S is a simple multiplicative factor that accounts for the effects of water stress as:

$$K_S = \max(\, 0.0, \min(1.0, (SWC\text{-}WP)/(SP\text{-}WP))) \qquad \text{Eq. [9]}$$

which assumes a value between zero (i.e. complete water-stress with zero transpiration) and 1.0
(i.e. no water stress and maximum transpiration). Thus, we model the expression of water stress using a linear reduction in actual transpiration, T_a, as soon as the *SWC* becomes less than the stress point, *SP*. Other stresses such as nutrient deficiencies, heat, cold, insects and disease, have been ignored in these calculations. The default setting of $SP = ½\,(FC + WP)$.

Evaporative losses from the bare soil, E_S, are calculated using a simple two-stage model similar to that of Ritchie (1972). E_S is assumed to be proportional to the evaporative demand, being flux-limited
(< 2.6 mm/d) for the first two days, and thereafter decreasing as the square-root of the time, t_L (days), since any significant irrigation or rainfall (i.e. since *IR* or *RF* > 5 mm/d) occurred. Thus, soil evaporation is modelled as:

$$E_S = \min(2.6, \min(\, 1.0, (1.2\text{-}K_C)^2/\sqrt{t_L})\, ET_O), \qquad \text{Eq. [10]}$$

with the effect of shade from the leaf canopy being embodied in the crop factor term. Similarly, evaporative losses from the vegetative (grassed) part of the understorey are modelled as:

$$E_V = \min(\, 1.0, (1.2\text{-}K_C)^2\,)\, K_S\, ET_O. \qquad \text{Eq. [11]}$$

In this case we make the simple assumption that the understorey vegetation exhibits the same water-stress response as the tree and vine crops. This assumption is necessary since we are using a simple tipping-bucket approach that cannot separate the grass from the trees. We assume a fraction of the understorey is covered in vegetation, α_V, and so the total evaporative loss from the understorey (ground), E_G, is modelled as:

$$E_G = \alpha_V\, E_V + (1\text{-}\, \alpha_V)\, E_S \qquad \text{Eq. [12]}$$

A simple spreadsheet model has been developed using Eqns 12-20 (S Green, pers comm).