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AGR30938 Do tree-pasture systems accumulate more soil carbon? A pilot project

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Executive Summary

Tree-pasture (TP) systems involving widely spaced planted trees on pastoral land have been a widespread feature of New Zealand's pastoral hill country for 50^{+} years. The primary purpose of the trees is to reduce the occurrence of erosion processes to enable the continuation of livestock farming. There has been increasing interest in the potential of trees at a range of densities to sequester carbon (C) in above- and below-ground components to mitigate against increasing atmospheric concentrations of greenhouse gases (GHG). Soil is a significant reservoir of C globally. Of the very few studies that have determined soil C mass in TP systems, sampling has been restricted to the surface and up to 300 mm depths. This study aimed to determine if TP systems accumulate more soil C than open pasture (OP) systems to 1 m depth via field sampling; and to quantify their influence on farm GHG emissions and emissions intensity via modelling.

Field studies were conducted in TP systems aged 14-16 years at four geo-climatically different North Island sites. Trees of poplar (*Populus* spp.) were at two sites at Tikokino in central Hawke's Bay and Woodville in southern Hawke's Bay; trees of alder (*Alnus* spp.) were at the other two sites at Ruakura in Waikato and Poukawa in central Hawke's Bay. At each site, trees were arranged in partial-Nelder radial planting designs. Five densities ranging from Low (67-112 stems per hectare [sph]), across sites) to High (734-1276 sph) were selected. Adjacent Open areas in the same paddock were selected. The main sampling was conducted in November/December 2012 to a depth of 1 m for total root mass, soil C concentration and soil bulk density. Depth increments were 0-75, 75-150, 150-300, 300-600 and 600-1000 mm. Farm-scale models FARMAX® and OVERSEER® were used to explore seven farming scenarios comprising OP and six TP systems to quantify GHG emissions.

Background data on the trees, pastures and soils from each of the Nelder sites collected in the first five years following planting indicated that tree density had negligible effect on a range of soil attributes at the four sites. This was likely because the trees were young, with low litter inputs and fine root tissue turnover. It also indicates that the field sites were reasonably uniform at tree establishment.

In the main sampling, total root mass density (RMD) was 3- to 7-fold greater in TP than OP systems at all sites except at Ruakura where no significant difference in RMD between systems was detected. There were very few differences in RMD across tree stem densities. RMD decreased markedly with soil depth at all sites except Ruakura.

Highest mean total C mass to a depth of 1 m was estimated at Ruakura and Tikokino of 300-410 t C/ha, compared with 160-200 t C/ha at Poukawa and Woodville. Across all sites, C mass within a depth of 0-300 mm ranged from 48% to 61% of total C within the 1 m profile. Thus there are substantial C stocks below the 300 mm depth considered standard for IPCC soil C accounting. At Tikokino, total C mass in the soil of the OP system was 31% greater than in the TP system, as it was at Woodville with the OP being 23% greater than in the TP system. In comparison, at Ruakura and Poukawa there was no difference in C mass between the OP and TP systems, but there was a trend of higher C mass in the TP than OP systems at both sites. The key factor explaining these differences would appear to be the tree species, with poplar at Tikokino and Woodville, and N-fixing alder at Ruakura and Poukawa. The study suggests that tree species over-rode differences in primary pasture production levels (Ruakura and

Woodville > Tikokino and Poukawa) and soil type (Ruakura and Tikokino with volcanic soils vs. Poukawa and Woodville with sedimentary soils).

This study suggests that tree species may be an important factor influencing the C cycle and C accumulation in soils and needs to be added to the factors considered in the building of our soil C inventories, in addition to the C stored in the above- and below-ground biomass of the trees. Estimates of the amount of C stored in the tree will be determined by tree age, and also by the tree density, which will vary widely depending on the erosion type requiring stabilisation.

The modelled OP farm system had a higher livestock carrying capacity (13.4 stock units (SU)/ha) compared with the modelled TP scenarios that ranged from 11.9 to 12.5 SU/ha. Total DM intake (incl. poplar supplementation in some TP scenarios) was 7.91 t DM/ha for the OP and 6.98 to 7.36 t DM/ha for the TP scenarios, with associated gross margins of $761/ha and $669 to 796/ha, respectively. The shelter benefits from ewes having free access to the tree land blocks were captured in reduced lamb losses. The additional intake from tree cuttings provided for greater reproductive efficiency, with lambing percentages increasing from 132% (OP) to 154% for two TP scenarios. Estimates of total GHG emissions in the OP system were 4.8 t CO_2-e/ha compared with 4.2 to 4.4 t CO_2-e/ha in the TP scenarios. GHG emissions intensity per kg of meat and fibre produced was 15.9 kg CO_2-e/kg in the OP and 14.5 to 15.7 kg CO_2-e/kg in the TP systems. This reduction is largely because of the TP system maintaining or improving animal productivity with a reduced stocking rate.

The annual reduction of 567 CO_2-e/ha/yr is significant when aligned with the changes in C in the soil and stored in the tree biomass over time. As the quest for further productivity gains in the sheep and beef sector through on-going advances in fecundity, lamb survival to weaning, live weight gain and longevity continues, these advantages are likely to become larger with a TP system that is better able to provide the living environment required for these gains to be captured by the farmer.

The results carry key assumptions including: 1. A number of potential benefits of TP systems were excluded from the current modelling exercise, e.g. reduced soil losses, soil stabilisation, enhanced animal welfare; 2. Care should be taken in extrapolating these C mass measurements to hill slopes and other regions where wide-spaced trees are used extensively.

Recommendations from this study include: 1. In considering the influence of TP systems on soil C stocks, soil properties should be measured to at least 1 m depth; 2. A more detailed study is required to explore the factors contributing to the difference in soil C stocks between the poplar-TP system compared with the alder-TP system; 3. Inclusion of these and the C stocks in the tree biomass should be part of any future scenario testing, thereby strengthening our knowledge on the impacts of tree-pasture compared with open pasture systems on farm system scale GHG balances.

1. Introduction

The carbon (C) in soil organic matter represents a significant reservoir of C within the global C cycle. It has been estimated to account for 1200−1550 Pg-C to a depth of 1 m, and 2370−2450 Pg C to a depth of 2 m (Eswaran *et al.* 1995; Lal 2004). Comparative estimates of organic C contained in living biomass (560 Pg) and atmospheric CO_2-C (760 Pg) indicate that a small shift in the soil organic C pool has the potential to have a significant impact on atmospheric concentrations (Lal 2004). For example, a 5% shift in the amount of soil organic C stored in the 0−2 m soil layer could potentially reduce atmospheric CO_2-C by up to 16%. This represents a potential mitigation that for many New Zealand soils would also add natural capital (Dominati *et al.* 2010). Recent studies in New Zealand indicate that some pastoral soils (dairy on lowland) have lost 0.6 to 1 ton of C/ha/year, while others (dry stock and hill land) have gained C over the last 20−25 years (Schipper *et al.* 2007; Schipper *et al.* 2010).

The biggest threat to the on-going accumulation of C in hill land pasture soils is erosion (Lambert *et al.* 1984; Douglas *et al.* 1986; Blaschke *et al.* 1992; Basher *et al.* 2008) because it influences the soils' natural capital (C) stocks (Dominati *et al.* 2010). Hill land (slopes >15°) covers 10 million ha of the country. Slight to moderate erosion affects all this country (Mackay 2008; Lynn *et al.* 2009). Almost 20% of hill land is prone to severe or extreme erosion. Upwards of 75% of 1.5 million ha in Maori collective ownership has moderate to extreme limitations to use. Erosion has been identified as the biggest environmental threat to the sheep and beef industry (Petersen 2012). Millions of ha of hill land have had soil conservation plans prepared to address soil erosion over the last 50+ years (Manderson *et al.* 2007), with wide-spaced tree planting one of the major conservation practices undertaken (Thompson and Luckman 1993; Cairns *et al.* 2001).

Thousands of hectares of wide-spaced poplar (*Populus* spp.) and willow (*Salix* spp.) trees are planted in hill pastures annually to reduce the risk of erosion and protect natural and built capital improvements (Wilkinson 1999; Douglas *et al.* 2006b; McIvor *et al.* 2011; Douglas *et al.* 2013). Other species such as wattles (*Acacia* spp.), gums (*Eucalyptus* spp.) and alders (*Alnus* spp.) are planted at wide spacings for soil conservation, but they are used much less frequently (Van Kraayenoord and Hathaway 1986b). The stem density (stocking rate) of mature, wide-spaced trees on pastoral hill country is usually less than 50 stems per hectare (sph) (Hawley and Dymond 1988), equivalent to 14 m spacing, although density can vary considerably depending on the type and severity of erosion.

There is negligible information on the effect of wide-spaced tree-pasture systems on pedogenesis, soil C sequestration, and stocks. In one of the few studies on the effect of tree-pasture systems, Guevara-Escobar *et al*. (2002) determined the influence of a poplar-pasture system on soil properties and C cycling (0-75 mm) in a paired site comparison (tree-pasture vs. open pasture) on a commercial farm. Among their results, they found that soil pH was higher (0.5-1.2 units) in the poplar-pasture than open pasture system and that organic C was similar in soils in both systems, or lower in the poplar-pasture system. There are always doubts about the uniformity of these paired sites, with concern trees are on a location with greater actual or potential erosion than the paired open pasture.

The provision of shelter and shade for animals is another emerging reason for greater tree planting on pastoral farms (McGregor *et al.* 1999). This is given additional momentum by questions from the market on animal welfare. Trees are an option for reducing the risk of stock losses from extreme climatic events and moderating extended weather extremes (e.g.

temperature) to protect capital stock and sustain animal growth rates. Since the economic analysis of poplar planting on steep hill country by Parminter *et al*. (2001), we have a better understanding of the influence of tree-pasture systems on livestock behaviour and performance. Betteridge *et al*. (2012) found animals with access to shade grazed longer each day than animals without shade, despite spending time under shade during the day. Ramirez-Restrepo *et al*. (2010) found that consumption of willow fodder reduced methane production of young sheep in one of two study periods. Such effects on the animal's environment and performance must have implications for greenhouse gas (GHG) emissions, but there appear to be no data on the effect of trees on specific GHG emissions (e.g. N_2O emissions from drier soils) and no data on the influence of a tree-pasture system on the GHG balance at a farm system scale.

Introducing wide-spaced trees to a pasture modifies the local climate (e.g. temperature, radiation, incident rainfall) resulting in a decrease in primary production and change in botanical composition of the pasture sward (Guevara-Escobar *et al.* 2000; Douglas *et al.* 2006a; Guevara-Escobar *et al.* 2007; Benavides *et al.* 2009; Clavijo *et al.* 2010), with the decline in the flow of pasture litter and root biomass entering the C cycle, compensated for by inputs of tree leaf litter and root biomass (Young 1997). How the exotic tree-pasture systems found in New Zealand hill land allocate C above- and below-ground compared with an open pasture system has received little attention. Furthermore, it is not clear what the tree-pasture system does, if anything, to the stability of the stored C, given that the pasture and leaf litter have different characteristics (Douglas *et al.* 2006a). Native grassland systems have more C stored below ground than a forest ecosystem, and land use changes from forest to grassland generally lead to increases in soil C (Guo and Gifford 2002). By exploring a greater depth of soil, it would be possible to determine if a tree-pasture system increases the potential amount of C that could be stored, or if it just shifts the distribution of soil C down the profile. Furthermore, C deeper in the profile is potentially more stable with longer residence times (Jobbágy and Jackson 2000; Rumpel *et al.* 2002; Omonode and Vyn 2006). Trees also change physical, chemical and biological properties of a soil that influence C cycling. A mature poplar tree increases soil pH by as much as 0.5 pH units (Guevara-Escobar *et al.* 2002). Trees reduce average soil temperatures and have more pronounced impacts on seasonal soil water balances (Wall *et al.* 1997; Douglas *et al.* 2006b). Bardgett (2011) points to the growing appreciation of the influence that the flow of C from the plant below ground through the root system has on the below ground microbial communities and the many biogeochemical processes driving the C cycle. All these factors have the potential to change the rates of C sequestration in soil by influencing the amounts and rates of C cycling through the agro-ecosystem.

2. Objectives

This study aimed to:

1. Determine the effect of established conservation trees at various densities (spacings) on soil carbon concentration and mass to a depth of 1 m in geo-climatically different environments in the North Island.
2. Define the main interactions in tree-pasture-livestock systems, and estimate the likely differences in GHG emissions from livestock in tree-pasture and open pasture (without trees) systems.
3. Model a representative hill country sheep and beef farm with several tree-pasture alternative farm management scenarios to determine their potential to alter total GHG emissions and emissions intensity on farm.

3. Materials and Methods

3.1 SITE SELECTION

Four tree-pasture sites were selected, comprising two in summer-moist (Ruakura, Waikato; Woodville, southern Hawke's Bay) and two in summer-dry (Poukawa and Tikokino, central Hawke's Bay) environments (Table 1). The Ruakura site was located at AgResearch's Ruakura Research Station, Hamilton, and the other summer-moist site was at AgResearch's Ballantrae Hill Country Research Station near Woodville. The Poukawa site was at Poukawa Research Farm, formerly owned by AgResearch, and now owned privately and managed by On-Farm Research. The Tikokino site was located on a privately owned farm. Trees at each site were at a range of tree densities arranged in a Nelder radial planting design (Nelder 1962). These designs enable a wide variation in stem density to be studied in a relatively small area of land.

Table 1. Characteristics of the four North Island sites with Nelder radial planting designs.

Attribute	Poukawa	Ruakura	Tikokino	Woodville
Environment	Summer-dry	Summer-moist	Summer-dry	Summer-moist
Location	39°45'18" S 176°43'29" E	37°46'34" S 175°19'27" E	39°50'16" S 176°18'28" E	40°18'57" S 175°50'23" E
Elevation (m)	53	42	354	129
Slope angle	<5°	Flat	Flat	<15°
Soil type	Matapiro silt loam	Te Rapa silt loam/humic silt loam	Takapau sandy loam	Raumati silt loam
Species	Alder	Alder	Poplar	Poplar
Planting date	Sept 1998	Sept 1998	Sept 1996[1]	Sept 1996

[1]assumed because records not found

The tree plantings used in this study were established in September 1996 (Woodville, Tikokino) and September 1998 (Poukawa, Ruakura) by AgResearch and New Zealand Plant and Food Research Ltd. to provide a science resource for exploring the long-term changes in the natural capital stocks and ecosystem services of a tree-pasture system. Poplar at Woodville and Tikokino was *Populus deltoides* Marshall x *P. nigra* L. clone 'Tasman' and trees were established by planting vegetative cuttings (2.5-3.0 m-long poles), a standard practice with *Populus* spp. (Wilkinson 1999). The alders at Ruakura and Poukawa were Italian alder (*Alnus cordata* Loisel. Duby) and were established by transplanting nursery-raised seedlings. There are no reports of the seedlings being inoculated. The trees at Woodville and Tikokino established satisfactorily, whereas at Ruakura and Poukawa, some young trees died, particularly at Poukawa. At these sites, replanting was conducted and establishment at Poukawa was facilitated with limited trickle irrigation. Trees at all sites received no known management except at Woodville and Tikokino, where trees were pruned at least once. All sites were grazed with livestock but few details on stock class, stock numbers, and grazing frequency and duration were found.

3.2 BACKGROUND DATA

Data from reports, unpublished file collections and computer records on soil nutrient and other relevant attributes collected at each site were sourced to provide background information and context for this study.

3.2.1 Ruakura

Soil test analyses were conducted on samples (0-75 mm depth) collected on 17 November 1999 and 1 June 2005 at a range of densities within the Nelder design (Power et al., unpubl.). Records indicate that the same locations within the design were sampled at each date. Open pasture sites were sampled from the end of the paddock adjacent to the widest spacing. It is assumed that these sites were in the same paddock as trees in the Nelder design. On 6-10 April 2000, samples were collected across three replicates at depths of 0-75, 75-150 and 150-300 mm and analysed for KCl-extractable nitrate-nitrogen (N), ammonium-N, and anaerobically mineralisable-N. Data collected up to 2000 included pasture yield, botanical composition, volumetric soil water content (VSWC (%); 0-150 mm depth using time domain reflectometry (TDR)) and tree height (m).

3.2.2 Poukawa

Standard soil tests were conducted on samples (0-75 mm depth) collected on 17 November 1999 from beneath trees at different densities and from adjacent pasture. The tests comprised pH and contents of Olsen P (ppm), K, Ca, Mg, Na and SO_4-S (ppm). Total N concentration and bulk density were also determined. In July/August 2001, bulk density and gravimetric soil water content were determined at depths of 0-75, 75-150 and 150-300 mm. The gravimetric data were converted to VSWC using individual bulk density values. Between 2 July and 20 August 2001, samples were collected at depths of 0-75, 75-150 and 150-300 mm and analysed for KCl-extractable nitrate-N, ammonium-N and anaerobically mineralisable-N. Data for pasture dry matter production and botanical composition, and tree height (m; January and August 2000) were sourced from excerpts of an untitled report (Power et al., unpubl.).

3.2.3 Tikokino

Soils were sampled to 75 mm depth in October 1997 and analysed for KCl-extractable nitrate-N, ammonium-N, mineralisable–N and total N concentration (Power *et al.* 1999). Gravimetric soil water content (%) was determined every 1-3 months from 15 November 1997 to 26 October 1999. Pasture production and botanical composition data, collected over 2 years, were obtained (Power *et al.* 1999). Tree height (m) was measured on 2 December 1999. Diameter at breast height (DBH, tree trunk diameter at 1.4 m above ground; cm) was measured, but no data were found.

3.2.4 Woodville

A range of analyses were conducted on soil samples (0-75 mm depth) collected on 27 November 1998 and 15 November 2000 in tree densities ranging from 0 (open pasture) to 1,100 sph. Pasture samples were collected from the same paddock as that comprising the trees and were likely taken at more than 20 m from any tree. Records suggest that soil at both times was sampled from the same tree-pasture areas. Bulk density and VSWC (converted from gravimetric measurements) were determined for random samples in the tree-pasture system on 3 September 1999. Pasture production was determined over almost three years (November 1998 – July 2001) and botanical composition was assessed for samples harvested on 7 December 1998. Tree height (m) and DBH were measured on 15 October 2000.

3.3 FIELD STUDY

3.3.1 Soil and root sampling

A preliminary assessment of the soil nutrient status across the tree density range at each site was conducted at Poukawa, Tikokino, and Woodville on 15 October 2012 and at Ruakura on 26 October 2012. At each site one transect (ray or spoke) of the Nelder design was selected that had healthy, well developed trees. Soil samples (5 x 25 mm diameter cores; 0-75 mm depth) were extracted at five positions along the transect, each midway between pairs of adjacent trees. Each pair of trees was separated by three trees, so that sampling occurred across the length of the transect, and hence covered the range in density from high to low. The sampling positions were arbitrarily defined as 1, 4, 7, 10 and 13, with one being at the high density end of the transect. No samples were collected from adjacent open pasture areas, without trees. Tree DBH in each pair was measured using a diameter rule (KDS Corporation; F10-02DM), and a tape was used to measure the distance between trees in each pair.

Main sampling of the sites was conducted at Ruakura on 26-28 November 2012, at Poukawa and Tikokino on 3rd and 4th December 2012, and at Woodville on 5th December 2012. This involved coring using a hydraulic hammer system in a tower mounted on the rear of a modified 4WD quad bike (Figure 1).

Figure 1. Hammer system in tower mounted on the rear of a modified quad bike for inserting soil cores. Core shown is 1050 mm length, 100 mm internal diameter.

Separate samples were collected at five depths (0-75, 75-150, 150-300, 300-600, 600-1000 mm) in five tree densities and in nearby open pasture for determination of soil carbon (C) and root mass. The depth ranges at shallow depths were relatively small because of the expected greater change in attribute values between depths than deeper in the profiles. Unlike the preliminary assessment, two adjacent transects were selected so that a series of approximate squares (combination of transects and arcs), with a tree at each corner, was generated from the innermost (centre or “hub” of the Nelder design) to outermost trees. Five of these were chosen to provide a range from high to low tree density (Figure 2), with trees in the innermost and outermost arcs excluded to minimise potential edge effects. The densities were arbitrarily termed Low, Low-medium, Medium, Medium-high and High, and their quantitative values are presented in Table 2. It was possible to select a wider range in tree density at Ruakura than at the other sites, which had similar values in each density category.

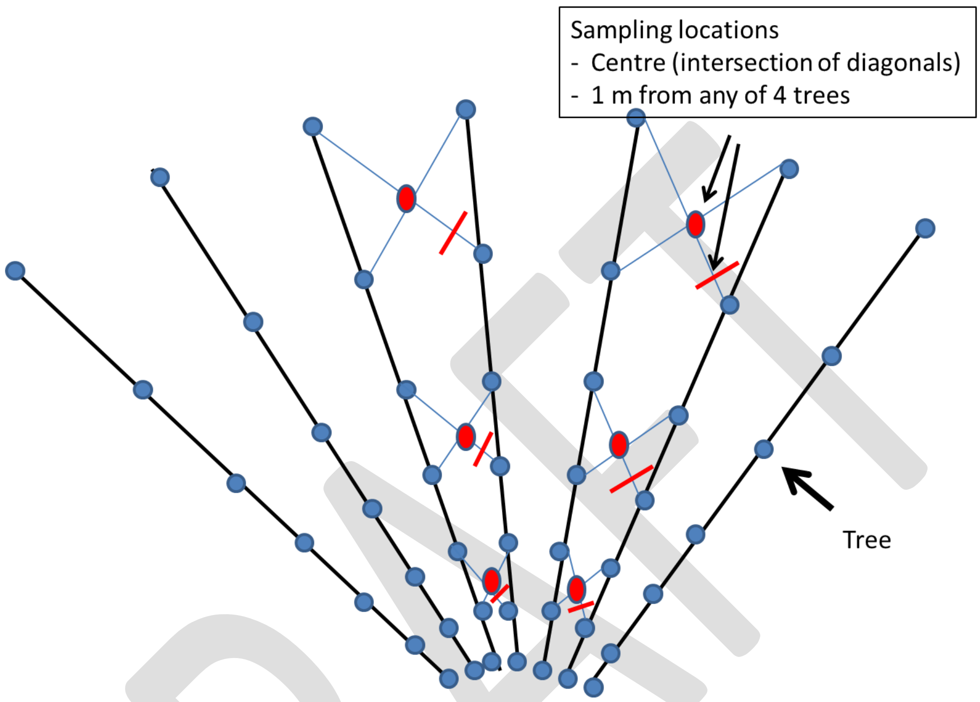


Figure 2. Sampling approach used in the main sampling in four Nelder radial planting designs in the North Island in November/December 2012. Three densities (High, Medium and Low) are shown for simplicity.

Table 2. Mean density (sph) of ordinal categories describing tree density in Nelder radial planting designs at four sites, averaged over two replicates.

Density	Poukawa (sph)	Ruakura (sph)	Tikokino (sph)	Woodville (sph)
Low	95	112	76	67
Low-medium	131	248	136	121
Medium	238	458	247	222
Medium-high	441	786	447	420
High	734	1276	777	818

Within each group of four trees, samples were collected at two positions: the centre, henceforth referred to as Centre, defined by the interaction of the two diagonals between the trees; and at 1 m along the diagonal from the left innermost tree looking towards the Low density trees. The Centre position increased in distance from any tree with decreasing tree density whereas the 1 m position was constant across all densities. There were two replicates of transect pairs at each site, giving a total of 20 sampling positions within planted areas. In nearby open pasture, there were three replicate sample positions. Samples for soil C comprised 3 x 25 mm diameter cores per position. The cores were obtained in depth increments by either placing removed cores on a cutting board and severing the samples to the appropriate length (depth), or removing samples from the same hole in stages. Soils at each depth were bulked for later analysis.

Samples for root mass determination were collected using two core diameters. It was originally proposed that a 100 mm internal diameter stainless steel core (1050 mm length) be used to obtain all samples, at the rate of one core sample per position to a depth of 1000 mm. The core was manufactured especially for the study by an AgResearch engineering team at Lincoln, and attached to the hydraulic hammer system described previously (Figure 1). This procedure was followed at Ruakura and worked successfully to depths of 1000 mm for many samples. However there were several cases where all the soil within 600-1000 mm depth was unable to be sampled because the machinery could not hammer the corer to the full 1000 mm depth. In these cases, the depth of penetration of the soil profile was estimated by measuring the length of a rod inserted into the cored hole with a ruler, to enable later calculation of soil volume sampled. At Poukawa, similar problems with penetration by the corer were encountered because of the very dry soil. Twelve of the 20 tree positions were resampled with 3 x 25 mm diameter cores and bulked by depth. Sampling in the three open pasture positions was satisfactory with the single 100 mm diameter core. The approach at Tikokino comprised using 3 x 25 mm diameter cores at all sampling positions and bulking samples at each depth. At Woodville, samples at two positions were obtained using the 100 mm diameter core, but the core was only able to be hammered to depths of 750 and 800 mm. Therefore, samples at all other positions at this site were obtained using 3 x 25 mm diameter cores.

Samples for determining bulk density were obtained at each site from beneath and beyond trees. In planted areas, Centre and 1 m positions were sampled at the Low, Medium and High densities in the two reps at each site. Both positions were sampled within depth increments of 0-75, 75-150, 150-300, 300-600 (Centre only) and 600-1000 mm (Centre only) by inserting a stainless steel ring (100 mm diameter; 50 mm (Ruakura only) or 75 mm deep) vertically in to a series of steps in pits excavated by hand. After insertion, the top of the ring was 0, 75, 200, 400 and 800 mm below the surface. Three replicates of adjacent pasture soil were sampled in the same way. The DBH of trees in each density group was measured using a rule as described previously.

3.3.2 Soil sample preparation and processing

3.3.2.1 Samples collected October 2012 (preliminary sampling)

The 20 samples (five per site) were submitted fresh in sealed plastic bags to Eurofins/NZLABS, Ruakura Research Centre, Hamilton. The laboratory prepared the samples and analysed them for pH (1:2.1 v/v water slurry), phosphate (P, Olsen extraction), SO_4-sulphur (phosphate extraction), Quick-test cations (Ca, K, Mg and Na using ammonium acetate extraction), organic C content (CrO_3 wet oxidation, colorimetric determination), organic matter content (organic C x 1.724 (Bemmelen factor)), total Kjeldahl N content (total Kjeldahl digestion, Flow Injection Analysis (FIA) colorimetry (excludes nitrate-N)), nitrate-N and ammonium-N contents (KCl extraction, FIA colorimetry), mineralisable-N content (nitrate-N + ammonium-N), and soil water content (dried at 105°C for 24 hrs).

3.3.2.2 Samples collected November/December 2012 (main sampling)

Bulk density: Samples were dried at 105^{o}C for 36-48 hours, and then weighed. Roots 1 mm diameter or greater and stones/pebbles were removed from the dried samples and weighed. Any nodules present on alder roots were included in the root component.

Roots: For all sites except Ruakura, roots (1 mm diameter or greater) were removed from fresh samples by hand and their fresh weight measured. They were then classified into six arbitrary weight classes from low to high (<0.2, 0.2-0.75, 0.75-1.5, 1.5-2.5, 2.5-5, >5 g) and 4-6 samples in each class chosen for washing to remove soil contamination. The chosen samples were dried at 70^{o}C for 24 hrs to determine dry weight. All root samples from the Ruakura site were washed, air-dried, and then dried overnight. In all cases, no distinction was made between roots of tree and herbaceous (pasture and weed) species.

Soil C: Samples were air-dried/oven-dried at approximately 30^{o}C for 24 hours and then passed through a 2 mm sieve. Each sample was mixed thoroughly and then a subsample placed in a 70 ml plastic vial. In total, there were 360 samples across the four sites. Samples were analysed for total carbon content (%) using a Leco CNS-2000 dry combustion analyser. This involved combustion at 1350^{o}C followed by detection of combustion gas (as CO_2) using infra-red absorption measurement.

3.3.3 Data collation and analysis

3.3.3.1 Background data

Relevant data from the four sites were collated and the soil nutrient data were plotted to show trends with tree density and differences between sites.

3.3.3.2 Preliminary soil nutrient status

The distance between pairs of trees at each site at arbitrary positions of 1, 4, 7, 10 and 13 was converted to equivalent tree density per hectare assuming that the distance between trees represented one side of a square. The density at each position was averaged across sites for graphical presentation, and ranged from 80 to 690 stems per hectare (sph). The range across sites for each arbitrary position was 657-751 sph for 1, 356-541 sph for 4, 204-308 sph for 7, 125-166 sph for 10, and 63-89 sph for 13.

3.3.3.3 Main sampling

DBH: For each site, measurements on each group of four trees in each of the two reps in the five densities were averaged and graphed to show trends from High to Low density.

Roots: For each of the non-Ruakura sites, root samples washed and dried were used to determine linear relationships between root dry weight (Y) and root fresh (washed) weight (X). These were $Y = 0.44*X – 0.05$ ($R^2 = 0.98$) for roots from Poukawa, $Y = 0.38*X – 0.08$ ($R^2 = 0.99$) for roots from Tikokino and $Y = 0.37*X – 0.01$ ($R^2 = 0.90$) for roots from Woodville. These relationships were used to determine dry weights of the unwashed root samples at each site, thereby providing complete datasets for root dry weight at all sites. For these sites and Ruakura, total core volume sampled at each depth was calculated using data for soil depth sampled, number of cores taken, and core radius. These data were used in conjunction with root dry weight to calculate root mass density (mg DM/cm^3).

Root mass density data for each site for the five depth ranges, covering 0-1000 mm, were analysed using analysis of variance using Genstat v13. Analyses were conducted assuming three model structures. The first comprised sources of variation of rep, depth, system (open pasture, tree-pasture), and depth x system interaction, and included all pasture and tree-pasture data, giving a total of 114 degrees of freedom (df). The second structure comprised all pasture data and the Centre location data for the tree-pasture system, giving a total of 64 df. The third structure comprised all tree-pasture data (Centre and 1 m locations), a total of 99 df. Normality of residuals was tested with the Shapiro-Wilk statistic. Data transformations using square root and natural logarithm were used to improve residual distributions in a number of instances. Sources of variation were regarded as significant when the F-test probability was < 0.05. Mean separation was achieved using the Least Significant Difference test at the 5% level. Means on transformed scales were backtransformed to the original measurement scale.

Bulk density: The volume of material (soil, stone, root) sampled within rings was calculated as 393 cm^3 at Ruakura and 589 cm^3 at the other sites. Mass of soil sampled was determined by deducting the mass of root and stone from total mass following drying. Densities of stone (assumed as 2.5 g/cm^3) and root (0.6 g/cm^3), together with their respective masses, were used to calculate volume occupied by soil, thereby enabling calculation of soil bulk density (BD). In the Low, Medium and High densities at each site, BD values determined at 300-600 mm and 600-1000 mm depths in the Centre location were assumed applicable for the adjacent 1 m location. This was supported by analyses of data for the three shallower depths, which found no significant differences in BD between locations. At each site, analyses also found no significant difference in BD at the Low, Medium and High densities, except at Tikokino ($P = 0.048$). Mean bulk density across these three tree densities ranged from 1.29 to 1.34 g/cm^3 at Woodville, 0.71 to 0.75 g/cm^3 at Tikokino, 0.74 to 0.80 g/cm^3 at Ruakura, and 1.27 to 1.33 g/cm^3 at Poukawa. In view of the small variation in BD between densities at each site and to ensure consistency in approach across all sites, values of BD for Low-medium and Medium-high densities were calculated by linear interpolation between values for Low and Medium, and Medium and High, respectively. BD data are not presented because they are a mixture of measured and interpolated values and were used only to convert soil C concentration to C mass. An exception is presentation of BD values for depths at each site to show general trends.

Soil C concentration: Data were subject to analyses of variance (three models) as described for root mass density. In preliminary examinations, data were analysed using multiple linear regression and exponential or asymptotic regression, on original and transformed scales. Results were generally unsatisfactory because of poor data fit, with percentage variance accounted for often being less than 40%.

Soil C mass: Carbon mass at each depth was calculated by multiplying soil C concentration (%) by BD (g/cm^3), and expressing in units of t C/ha. These data were subject to analyses of variance (three models) as described for root mass density.

Total soil C mass: Data for soil C mass were summed over the five depths to 1000 mm, and then analysed assuming the three model structures described previously. The reduced sample size arising from aggregation over depths resulted in lower total df in each analysis structure, being 22 df for the first structure, 13 df for the second structure, and 19 df for the third structure.

3.4 IMPACTS OF SILVOPASTORAL SYSTEMS ON GREENHOUSE GAS EMISSIONS

3.4.1 Background information and modelling assumptions

A representative farm in Manawatu was modelled to represent several silvopastoral scenarios. The baseline scenario (Open) comprised a hypothetical 368-ha farm located in the Pohangina Valley. This District was chosen due to previous silvopastoral research conducted in the area (Douglas *et al.* 2001; Guevara-Escobar *et al.* 2002; Douglas *et al.* 2006a; Douglas *et al.* 2006b; Guevara-Escobar *et al.* 2007), which facilitated the inclusion of local soil, climate and pasture growth data, along with numerous biophysical components of the system.

A North Island, Intensive Finishing Beef and Lamb New Zealand Economic Service Survey Class 5 farm (Beef and Lamb New Zealand 2013) was setup in conjunction with key parameters from a Western Lower North Island (WLNI) Farm Monitoring 2012 system (Ministry for Primary Industries 2013). In brief, a sheep and beef Class 5 Intensive Finishing farming system includes a high-producing grassland, carrying approximately 12 stock units per ha, with a supplementary winter fodder crop established on rolling topography. The WLNI model represents almost 400 sheep and beef farms located on the west coast of the North Island, south of New Plymouth. The modelled farm comprised a sheep breeding policy including imported lambs for finishing (an additional 32% of total lambs weaned on-farm), a cattle trading policy including beef-type bulls, initially purchased at 3 months of age, and selling excess hay produced on-farm.

3.4.2 Models Used

The whole-farm system models FARMAX® and OVERSEER® (herein Overseer) were used to examine the nutrient flow and nutrient balance and losses, as well as livestock emissions from sheep and beef farming scenarios in Manawatu. Farmax® Pro (version 6.4.6.07, www.farmax.co.nz; herein Farmax) was used to simulate the different sheep and beef Class 5 farming scenarios. The biological feasibility of the stocking policies for each farm scenario was determined using Farmax. The required balance between whole-farm feed supply and feed demand was obtained by adjusting the timing of lambing and livestock purchases to periods of adequate pasture growth and by using supplementary feeds (winter fodder crop and hay from excess pasture grown on-farm).

All farms were of equal size (effective area = 368 ha) and all feed was produced on-farm. The systems were assumed to be in steady state in terms of both opening and closing numbers of breeding ewes and corresponding body weights. Livestock units (SU) were defined according to feed consumed on-farm (dry matter intake; DMI) including supplemental feed (1 SU = 550 kg DM consumed, similar to the 6000 MJ metabolisable energy (ME) per year used by Overseer, White *et al*. (2010)).

The nutrient budget model Overseer (version 6.0, www.overseer.co.nz) was used to examine some of the environmental outcomes, with an emphasis on greenhouse gas (GHG) emissions from livestock on open pasture and tree-pasture systems. The GHG model built within Overseer was developed as a decision support tool for pastoral farmers and consultants, and is being used increasingly as a tool to estimate on-farm GHG emissions throughout New Zealand (Wheeler *et al.* 2008).

Despite the absence of silvopastoral options in the models, pasture yield and corresponding animal distribution on open pasture and pasture plus trees was based on the relative pasture yield achieved by each of the land blocks. Pasture yields were ranked relative to the rolling block (originally based on pasture yields set in Farmax). For the purpose of this modelling exercise, soil nutrients (i.e. P, K, S) applied to each land block were tailored to individual nutrient maintenance requirements as suggested by Overseer. The methods used to estimate on-farm methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions have been described elsewhere (Wheeler *et al.* 2008). Total annual GHG emissions represent the sum of all three sources, and are presented herein as CO_2 equivalents (kg CO_2-e) per ha (total emissions) and per kg of meat and fibre produced on-farm (emissions intensity).

3.4.3 Farming Scenarios

Seven farming scenarios were modelled and explored; open pastures without trees (Open) plus six tree-pasture systems. The latter scenarios included a tree-pasture system without any benefits from having the trees (Trees_0), three scenarios where the shelter benefits from having the trees were included (Trees_10, Trees_30, Trees_50), and two scenarios where the shelter plus added DMI from tree leaves were included (Trees_I100 and Trees_I25).

The shelter benefits represented a 10%, 30% or 50% reduction in lamb losses from pregnancy to weaning for Trees_10, Trees_30, Trees_50, respectively, similar to those reported by McWilliam *et al.* (2004) and Pitta *et al.* (2005). The shelter plus added intake included the consumption of young poplar leaves (Trees_I100; 9.1 MJ ME/kg DMI, recently dropped leaves; Douglas *et al.* (2006a)) and tree cuttings (Trees_I25; 11.3 MJ ME/kg DMI, intact leaves, 25% of the amount offered to Trees_I100; Douglas *et al.* (2006a)). The shelter benefits (i.e. reduced lamb losses) for these scenarios were similar to those of Trees_30. Poplar supplementation occurred over 60 days (March and April) including the mating period (started March 15).

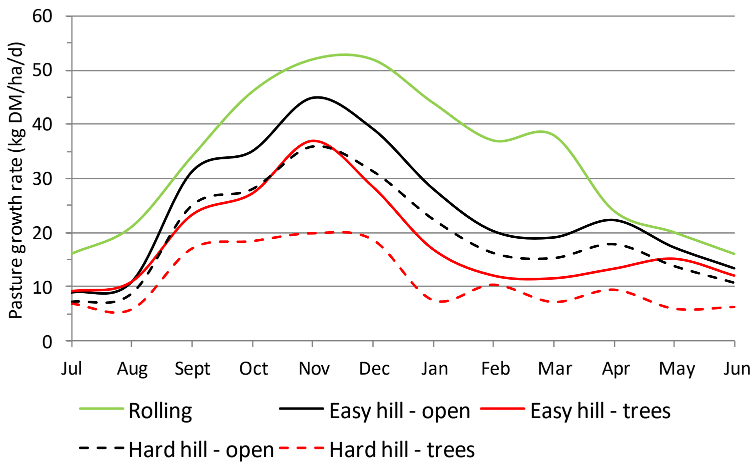
Livestock policies and farm physical characteristics from the Farmax modelling exercise were exported and used to parameterize Overseer, including the two 73.6-ha blocks of space-planted poplar (*Populus* spp.) trees (40% of the total effective area) present in the tree-pasture farming scenarios. For each of the six tree-pasture systems modelled, two levels of tree (Douglas *et al.* 2001) density (and consequential light interception and effective rainfall) were modelled, as follows:

- Three and five land blocks were established for the open pasture and tree-pasture scenarios, respectively.
- Blocks within farms included a rolling area (8 - 15° slopes; 73.6 ha; 20% of the total effective area), an easy hill area (16 - 25° slopes; 147.2 ha; 40% of the total effective area), and a hard hill area (> 25° slopes; 147.2 ha; 40% of the total effective area).
- To simulate the tree-pasture systems, within the easy hill area 50% of the land was in young, wide-spaced untended poplars, as described in Douglas *et al.* (2006a).
- Similarly, within the hard hill area, 50% of the land was in older, mature untended poplars, as described in Guevara-Escobar *et al.* (2007).
- Finally, to make all systems comparable from a pasture utilisation perspective, livestock numbers in each system were scaled to achieve maximum pasture utilisation using the ‘Modify’ tool in Farmax.

Monthly pasture growth rates for the rolling area were obtained from the Farmax Library (Manawatu ‘flat’, high quality); corresponding open pasture growth rates for the easy hill area were obtained from Douglas *et al.* (2006a) (Figure 1a). Hard hill areas were assumed to produce about 80% of the pasture grown in the easy hill area (Gillingham 1973). In addition, pasture growth rates under young poplars (0.75 of that produced in the open easy hill) were obtained from Douglas *et al.* (2006a); corresponding reduction in pasture growth rates under mature, more densely populated poplars (0.58 of that produced in the open hard hill) were obtained from Guevara-Escobar *et al.* (2007) (Figure 3a). The rolling block included the fodder crop and hay making from excess pasture growth. Mean pasture growth rates at the whole-farm scale for the Open and Trees_ scenarios are represented in Figure 3b.

Despite these assumptions, land blocks were set to establish potential farm carrying capacity and stock numbers, rather than set as separate management land units. The number of animals carried through winter, supplementary feed grown, and N applied for all seven scenarios are presented in Table 1. Nitrogen was applied on the rolling block in early September at a rate of 28 kg N/ha (mean response 10 kg herbage DM/kg N applied); no N was applied on the hill areas. For the purpose of this exercise, pasture from the rolling areas was considered of high nutritive value, whereas all pastures from the hill areas were considered of medium nutritive value; nutritive value is primarily set by altering the initial proportions of new growth to dead material in the canopy (Farmax).

a)



b)

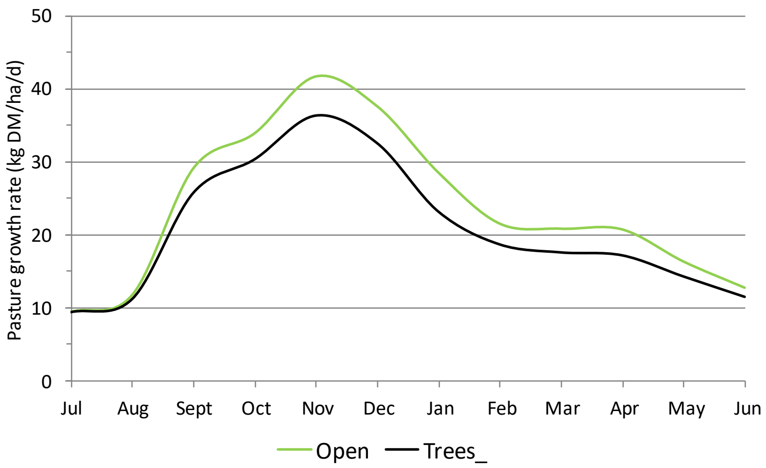


Figure 3. Monthly pasture growth rates (kg DM/ha/d at the end of each month) of a) the different land blocks considered within the farms, and b) the Open and tree-pasture (TP) sheep and beef farming scenarios in Manawatu.

Gross margins were calculated as the difference between total revenue (animal sales minus purchases) and expenses (hay making, forage crop, N cost, animal health, shearing costs, and interest on capital) (Farmax). It is important to note, however, that tree planting expenses and labour costs associated with feeding fresh tree leaves (tree cuttings) were not considered in the current modelling exercise.

4. Results

4.1 BACKGROUND DATA

4.1.1 Ruakura

Annual pasture production in the open, up to 2000, was 17.2 t dry matter (DM)/ha, with growth rates ranging from 15 kg DM/ha/d in April 2000 to 90 kg DM/ha/d in December 2000. There was negligible effect of tree density on annual pasture growth rate over the range 119 to 682 stems per hectare (sph). Percent grass decreased and percent weed increased with increasing tree density, whereas there was no change across the density range in percent legume, dead matter and moss. Mean annual VSWC (25-30%) was unaffected by tree density and seasonal values ranging from 20-25% in summer and autumn to about 35% in winter were also not influenced by tree density. Mean tree height across all trees increased from 0.5 m in May 1999 to 1.8 m in August 2000 and did not vary significantly with tree density.

Soil bulk density (0-75 mm depth) was approximately 0.6 g/cm^3 across all tree densities and was marginally greater than in open pasture (0.52 g/cm^3, Figure 4).

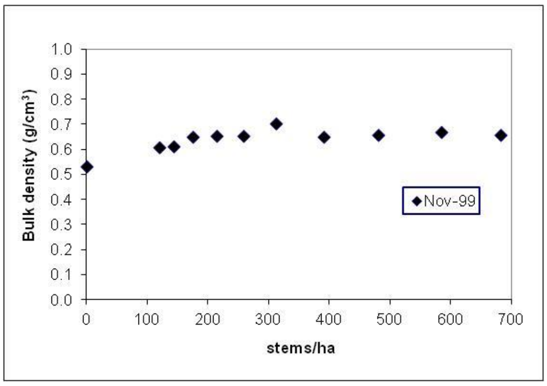


Figure 4. Soil bulk density (g/cm^3) at 0-75 mm depth in Nelder radial planting design at Ruakura in November 1999.

In November 1999, soil pH, K, Ca, Mg and Na were not affected by tree density (Figure 5). Olsen P decreased with tree density over the range 0-300 sph and was stable at 25 ppm at higher densities whereas SO_4-S was constant at low densities and increased slightly at densities exceeding 500 sph (Figure 6). Total soil N concentration of open pasture (1.0%) was greater than for all tree densities and there was negligible effect of tree density on this attribute (Figure 5). Results for June 2005 followed similar trends to those for November 1999 for attributes such as pH, Ca, SO_4-S and total N. Higher and more variable results were found for Mg and Na. Olsen P was the only attribute where June 2005 results at each density were 5-40% less than in November 1999 and the mean open pasture value was 47% less than in November 1999 (Figure 6). Soil nitrate-N, ammonium-N and mineralisable-N, 19 months after planting, were unaffected by tree density at any of the three depths (Figure 7).

4.1.2 Poukawa

Annual pasture production, assumed to cover the period October 1999 to January 2001, was 8.8 t DM/ha/yr, and growth rate ranged from 0 kg DM/ha/d in January 2000 and July 2000 to about 40 kg DM/ha/d in October 1999 and December 2000. Mean annual growth rate across the tree density range of 0 to 585 sph was mostly 18-20 kg DM/ha/d and was not affected by tree density. With increasing tree density, percent grass decreased from 75% to 65% and percent weeds and legumes increased very slightly. Percent pasture dead matter (approximately 10%) and moss (0%) were stable across the density range.

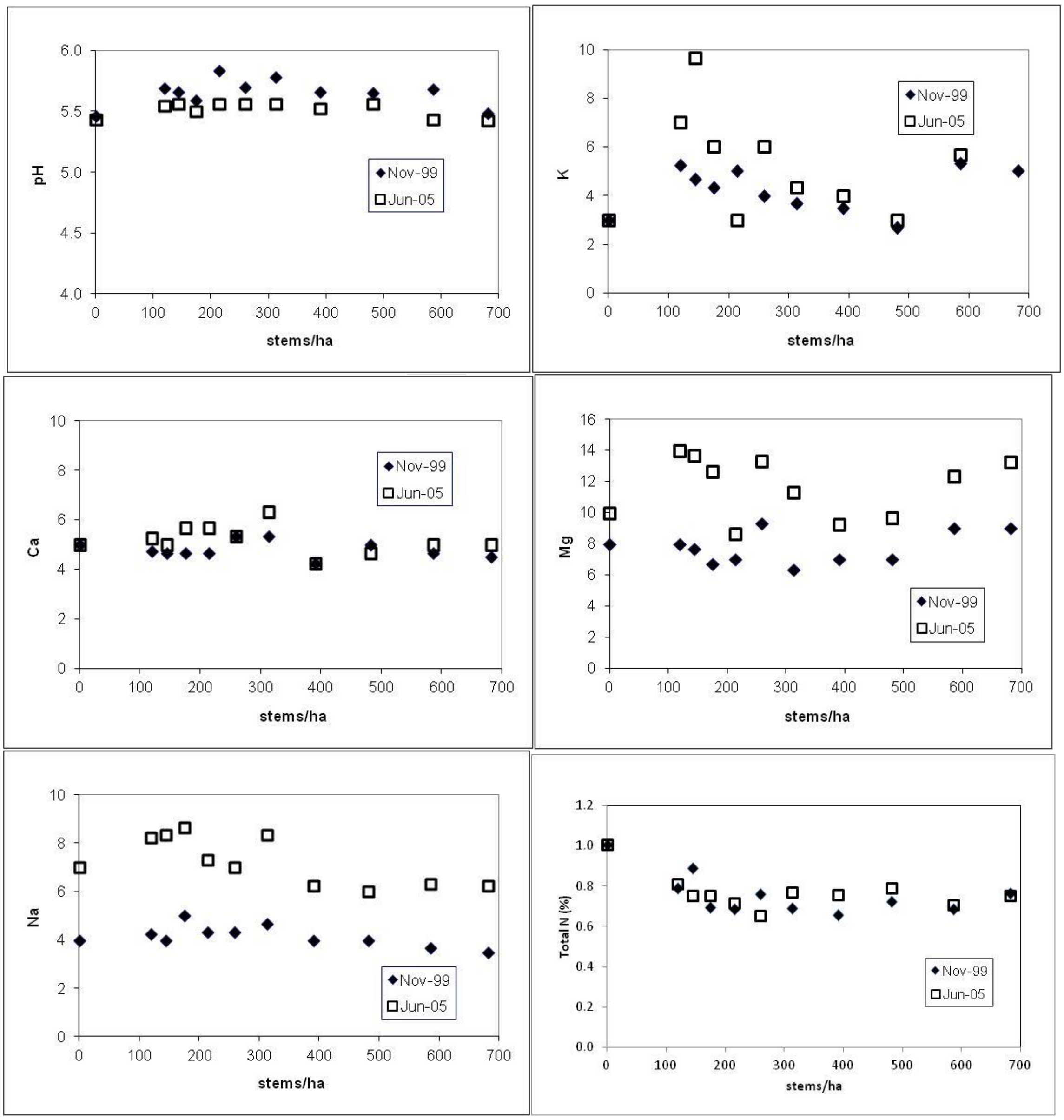


Figure 5. Soil pH and cations of K, Ca, Mg and Na (Quick-test units) at 0-75 mm depth in Nelder radial planting design at Ruakura in November 1999 and June 2005.

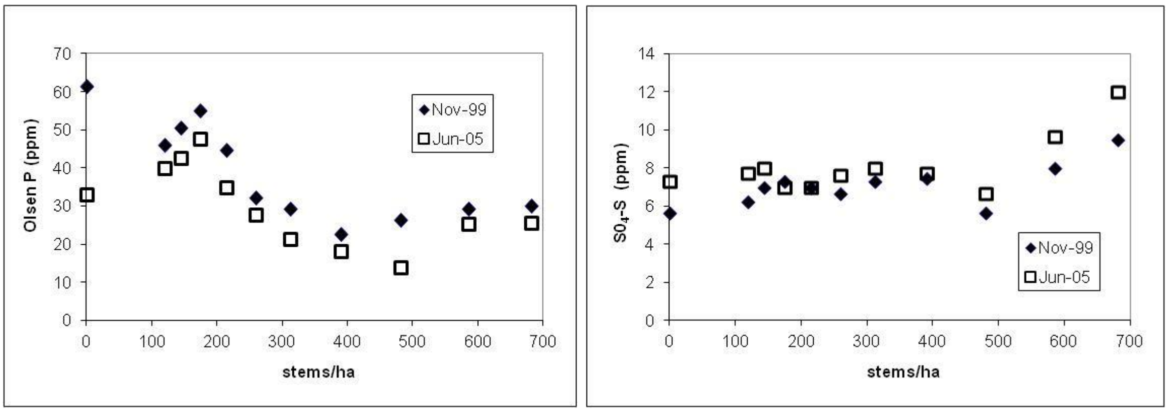


Figure 6. Soil Olsen P and SO_4-S status (ppm) at 0-75 mm depth in Nelder radial planting design at Ruakura in November 1999 and June 2005.

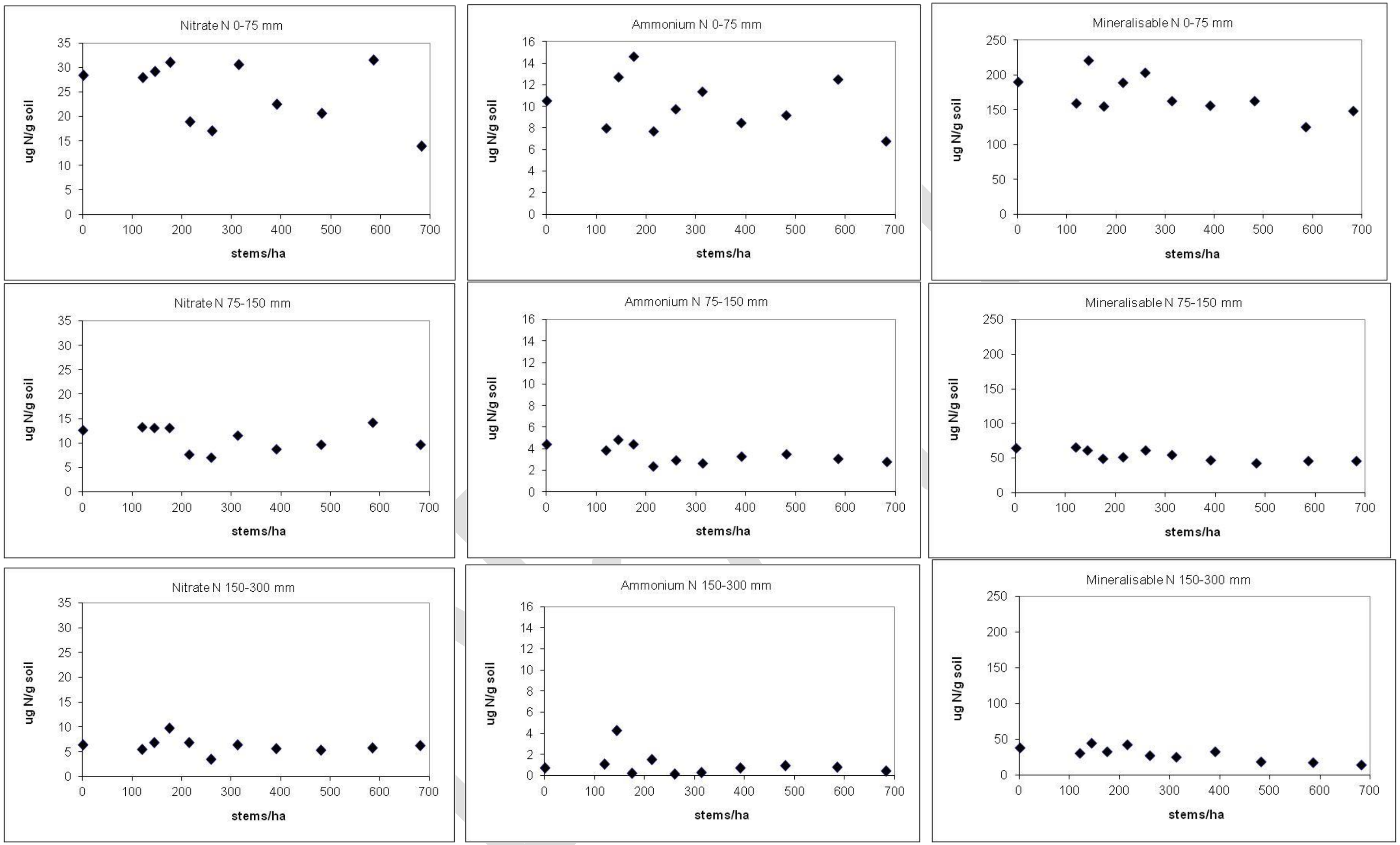


Figure 7. Soil nitrate-N, ammonium-N and mineralisable-N at three depths in Nelder radial planting design at Ruakura in April 2000.

Bulk density was approximately 0.6 g/cm^3 across the density range in November 1999 and 1.0 g/cm^3 in July 2001, with values in open pasture being slightly less than at any tree site (Figure 8).

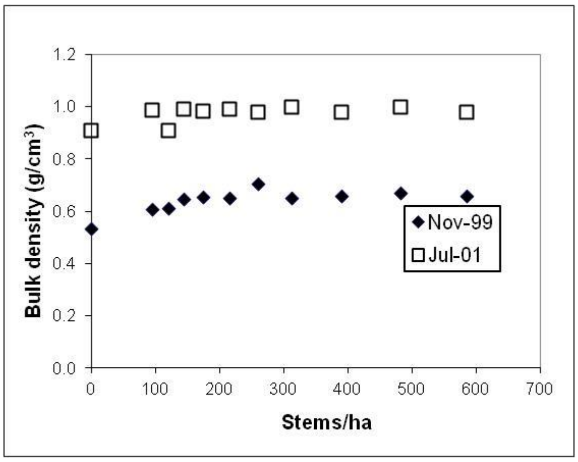


Figure 8. Soil bulk density (g/cm^3) at 0-75 mm depth in Nelder radial planting design at Poukawa in November 1999 and July 2001.

Soil pH was unaffected by tree density in November 1999 and July 2001, and over this 20-month period, pH often increased by about 0.3 units (Figure 9). There was no effect of tree density on contents of Ca, Mg and total N concentration (Figure 9). Open pasture sites had higher values than tree sites in the Nelder design for Olsen P (28 vs. 10-15 ppm), K (23 vs. 8) and SO_4-S (7.0 vs. 2.5 ppm), whereas tree sites had higher values than pasture sites for Na (9.5 vs. 6.1) (Figure 10). Mean VSWC and bulk density in July/August 2001 were unaffected by tree density at any of the three depths (Figure 11). Tree density had no influence on nitrate-N, ammonium-N and mineralisable-N at depth increments within 0-300 mm (Figure 12).

4.1.3 Tikokino

Across all tree densities, mean annual pasture production was 7.0 t DM/ha in Year 1 (1997/98) and 11.8 t DM/ha in Year 2. In both years, production decreased with increasing tree density, reducing from 7.5 t DM/ha/yr at 0 sph to 6.0 t DM/ha/yr at 670 sph in Year 1 and 13.5 t DM/ha/yr at 0 sph to 10.0 t DM/ha/yr at 670 sph in Year 2. Averaged over years, percent grass decreased and percent weed and percent moss increased, with increasing tree density. Percent legume and percent dead pasture were not affected by tree density. Mean gravimetric soil water content was 50% in Year 1 and 70% in Year 2 and did not vary with tree density.

Total soil N concentration varied between 0.89 and 1.07% and was unaffected by tree density (Figure 13). There was a trend of decreasing nitrate-N with increasing tree density although the value at 420 sph was a significant outlier to this trend (Figure 13). Ammonium-N and mineralisable-N were unaffected by tree density (Figure 13).

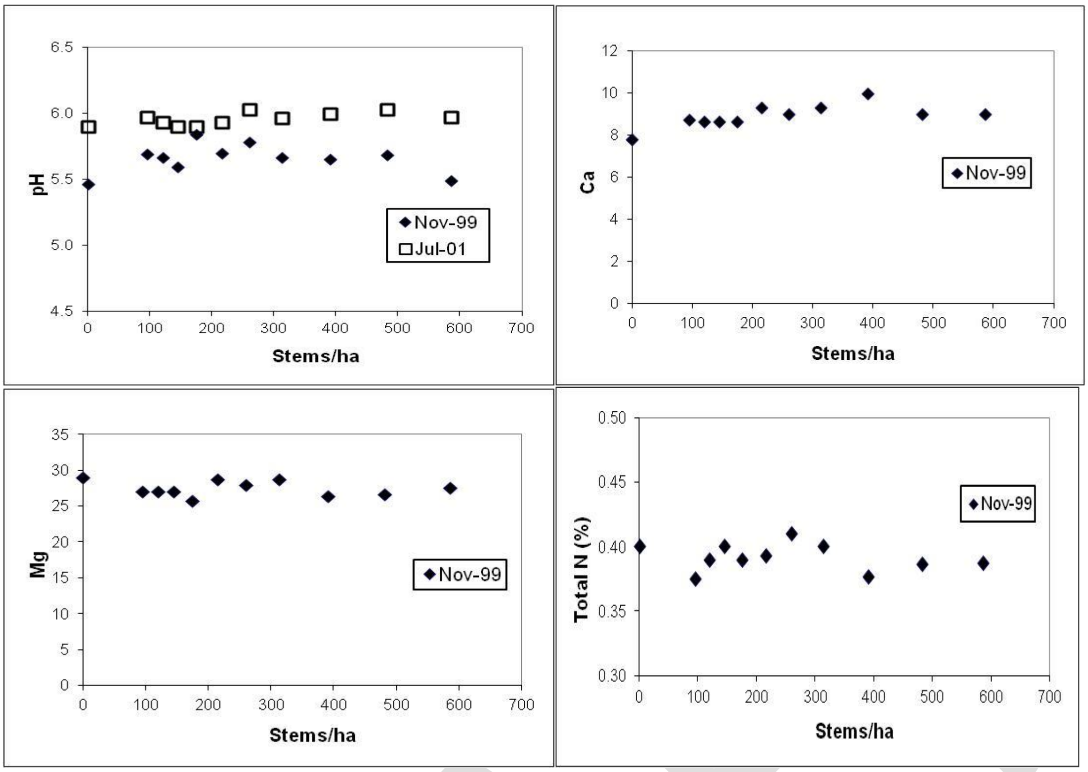


Figure 9. Soil pH, cations of Ca and Mg (Quick-test units), and total N concentration (%) at 0-75 mm depth in Nelder radial planting design at Poukawa in November 1999 and July 2001 (pH only).

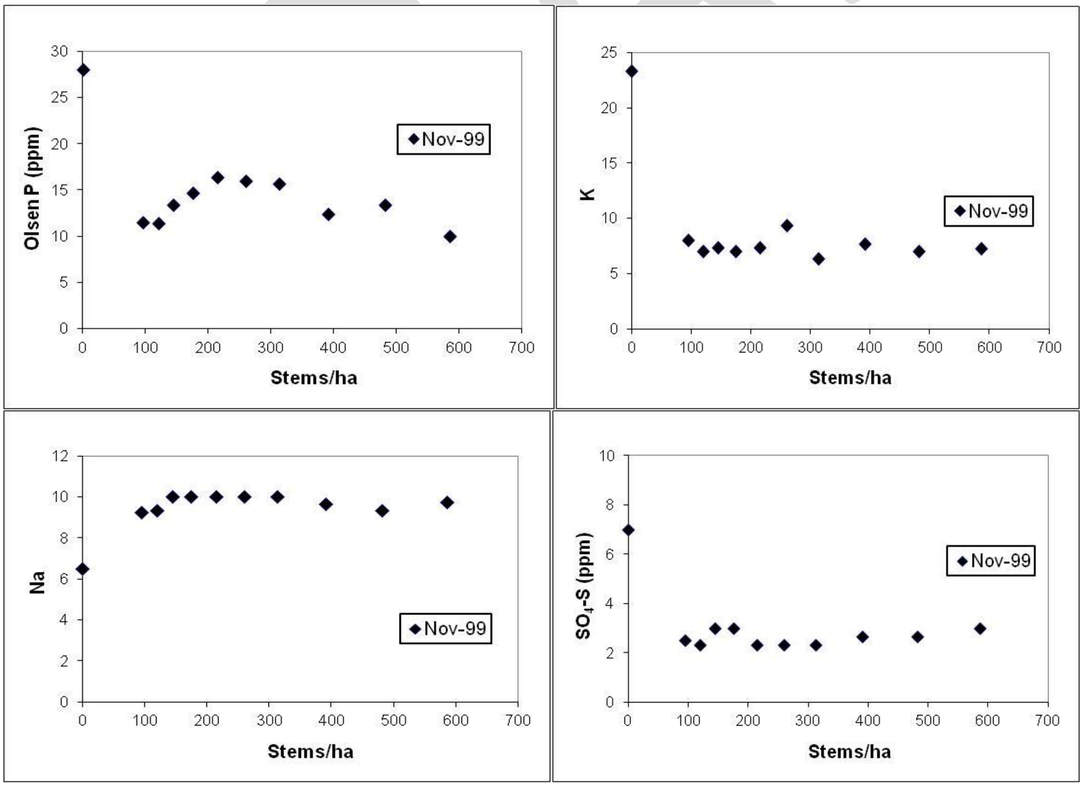


Figure 10. Soil Olsen P (ppm), cations of K and Na (Quick-test units) and SO_4-S status (ppm) at 0-75 mm depth in Nelder radial planting design at Poukawa in November 1999.

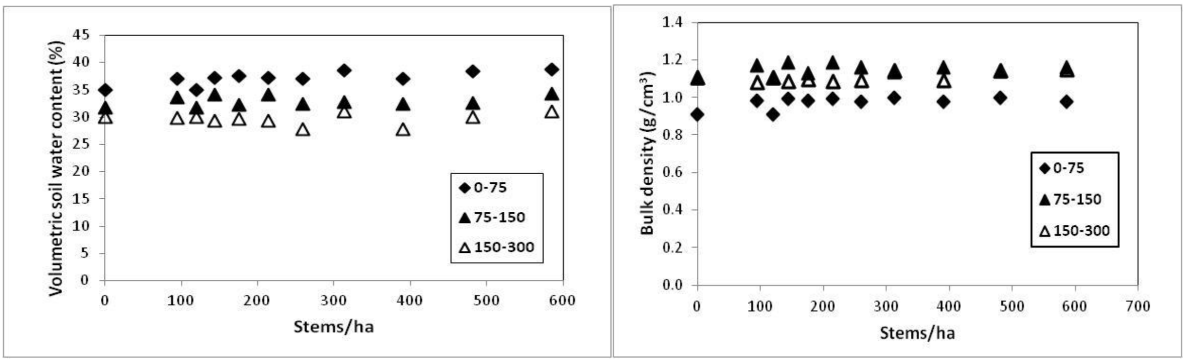


Figure 11. Volumetric soil water content (%) and soil bulk density (g/cm^3) at 0-300 mm depth in Nelder radial planting design at Poukawa in July/August 2001.

4.1.4 Woodville

Annual pasture production was 13.1 t DM/ha in Year 3 (1998/99) and 17.6 t DM/ha in Years 4 and 5 and in each year, there was no consistent effect of tree density on production. Botanical components in December 1998 averaged 72% for grass, 13% for legume, 10% for weed and 5% for dead matter, and data plots indicated that tree density had negligible effect on any of the attributes (not presented). Tree height and DBH were not affected by tree density over the range 59 to 1,100 sph and averaged 7.4 m and 9.1 cm, respectively.

Soil bulk density of randomly selected sites in the tree-pasture Nelder design in September 1999 averaged 0.74 g/cm^3 (se = 0.02) and mean VSWC at the same time was 0.50% (se = 0.02). Results for pH, Olsen P, K, Ca, Mg, Na, and SO_4-S in November 1998 and November 2000, and anion storage capacity in November 1998, were highly variable and there was no apparent relationship with tree density (Figure 14). Values for K and Ca were similar at each of the two sampling times whereas temporal variation was greater for attributes such as pH, Olsen P, Na and SO_4-S. Most values for pH, Ca, Mg and Na in November 2000 were lower than in November 1998. In contrast, Olsen P status was often greater in November 2000 than at the earlier sampling. Organic carbon content and organic matter content were the only attributes unaffected by tree density (Figure 15).

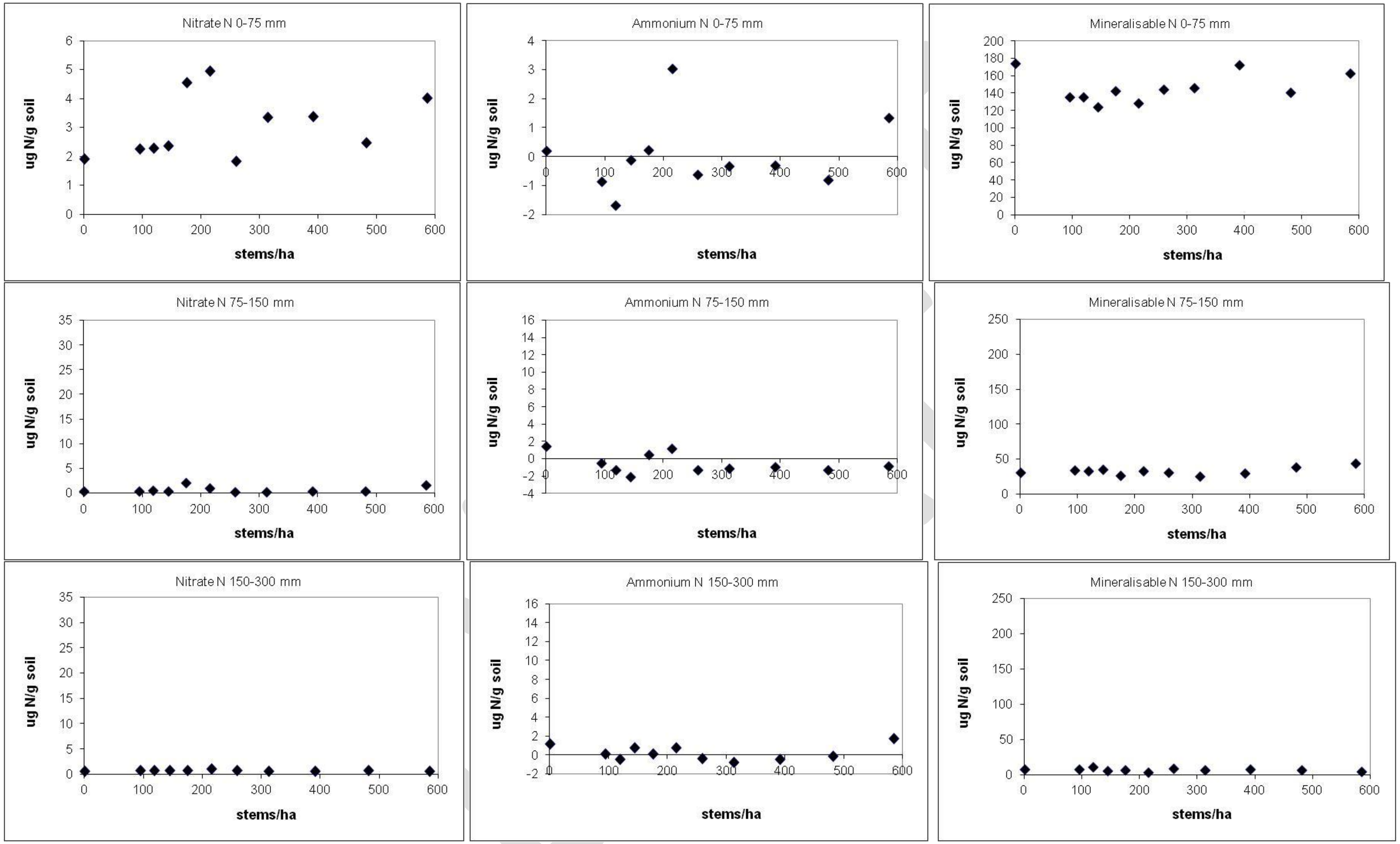


Figure 12. Soil nitrate-N, ammonium-N and mineralisable-N at three depths in Nelder radial planting design at Poukawa in July/August 2001.

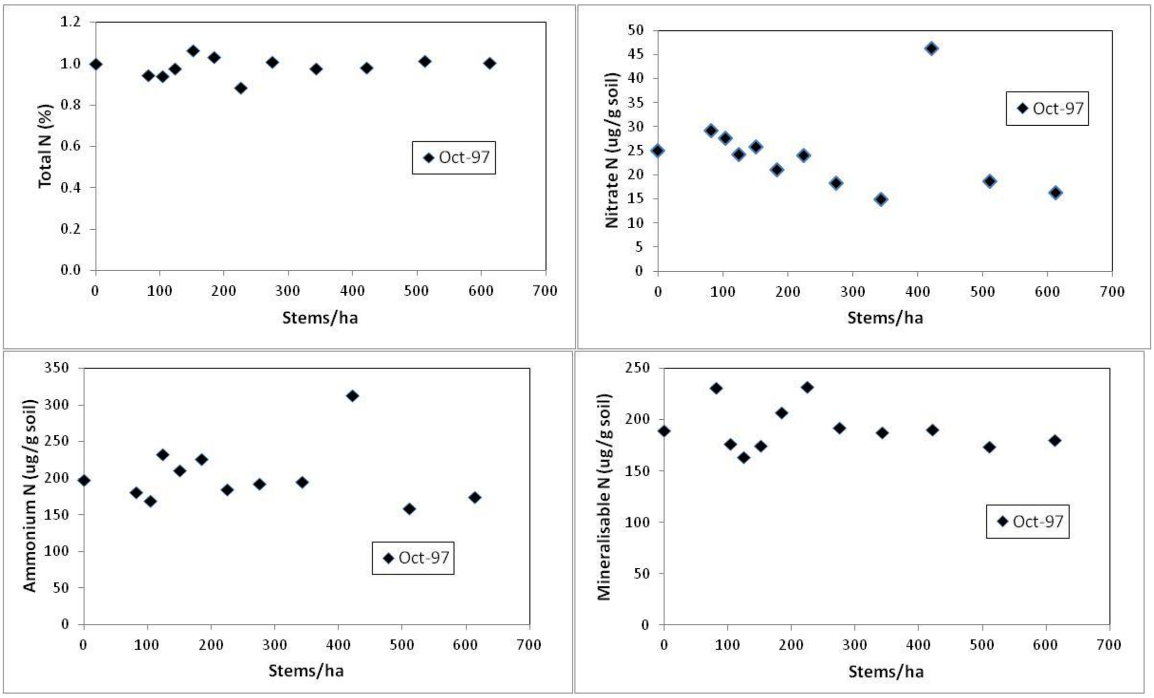
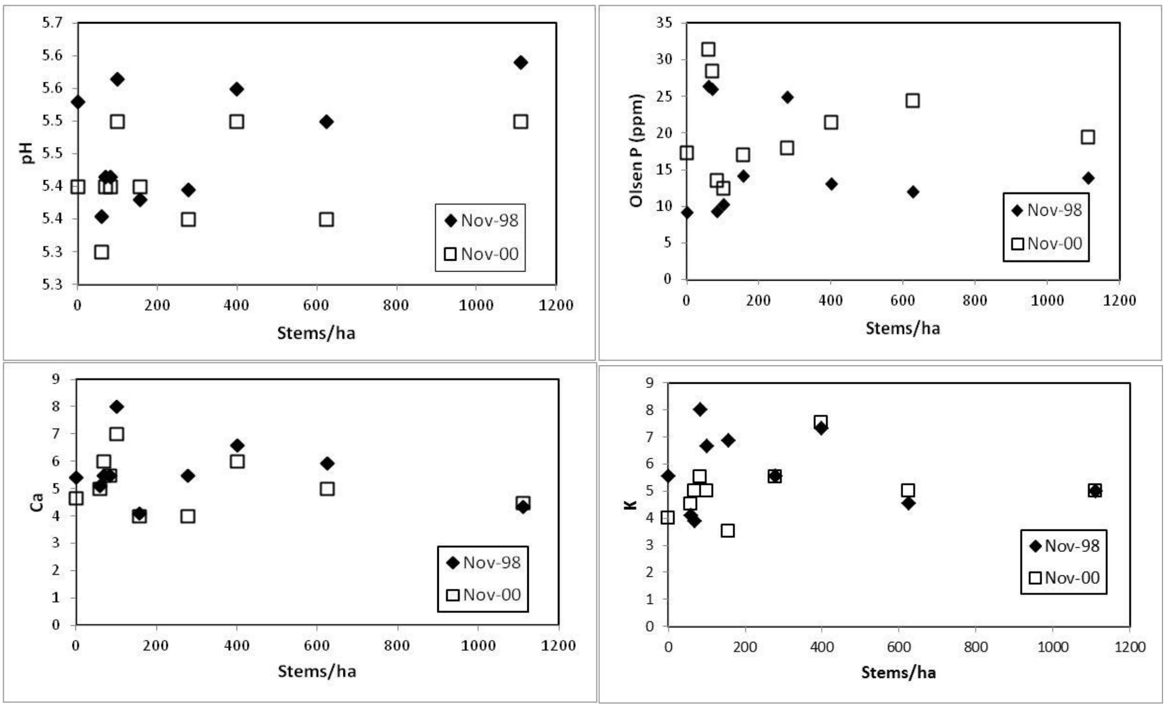


Figure 13. Total soil N concentration (%) and contents of nitrate-N, ammonium-N and mineralisable-N (ug/g) at 0-75 mm depth in Nelder radial planting design at Tikokino in October 1997.



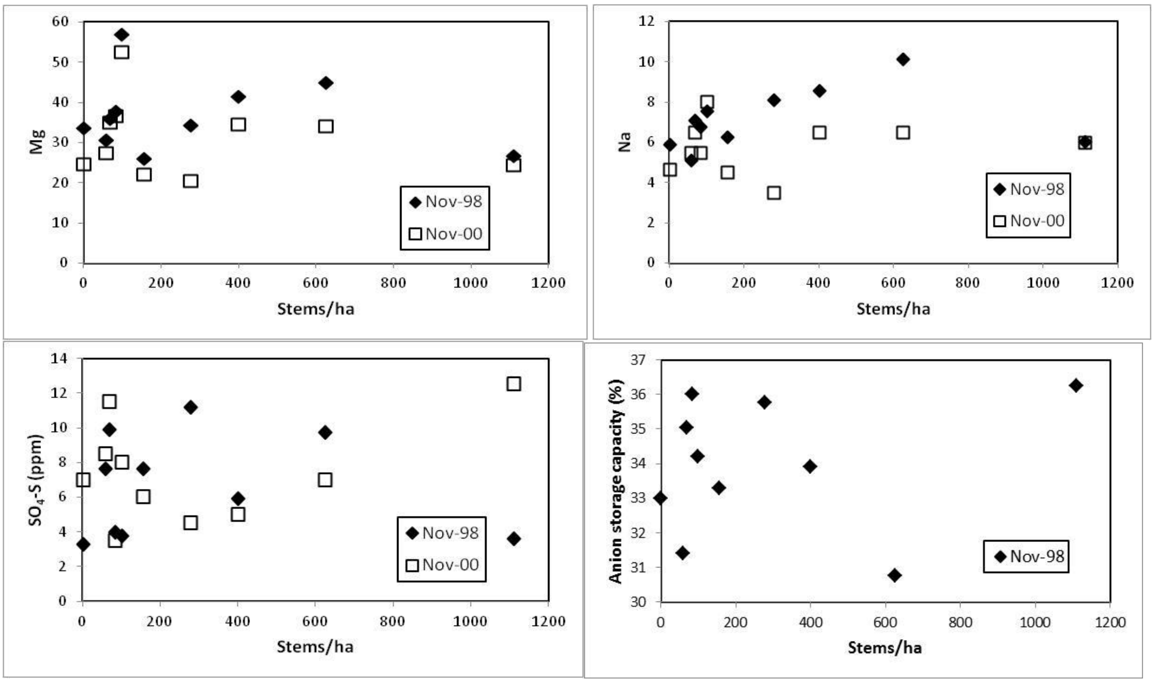


Figure 14. Soil pH, Olsen P (ppm), SO_4-S (ppm), cations of Ca, K, Mg and Na (Quick-test units) and anion storage capacity (%) at 0-75 mm depth in Nelder radial planting design at Woodville in November 1998 and November 2000.

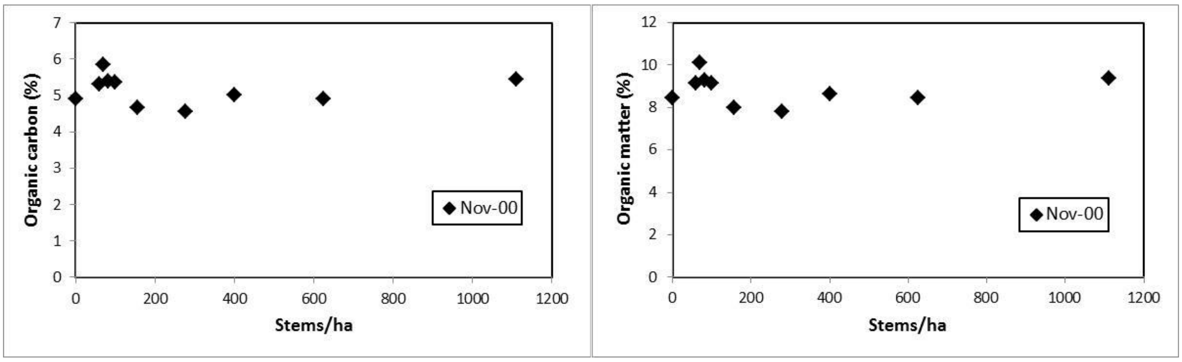


Figure 15. Organic carbon and organic matter content (%) at 0-75 mm depth in Nelder radial planting design at Woodville in November 2000.

4.2 FIELD STUDY

4.2.1 Preliminary soil nutrient status

Attributes varied in their response to tree density within and between sites. At each site, tree density had negligible effect on soil pH and concentrations of organic carbon, organic matter, and total N, and soil water content (Figures 16 and 17). Of these attributes, pH varied least between sites with all values ranging between 5.1 and 6.6. In contrast, values of organic carbon, organic matter and total N were about 2-fold greater at Tikokino than at the three other sites. For example, across densities, organic carbon at Tikokino was 8.1-10.6% compared with 3.9-6.1% at the other sites. Soils at Tikokino also had similar or higher values of SO_4-S and Ca than those at the other sites (Figure 18).

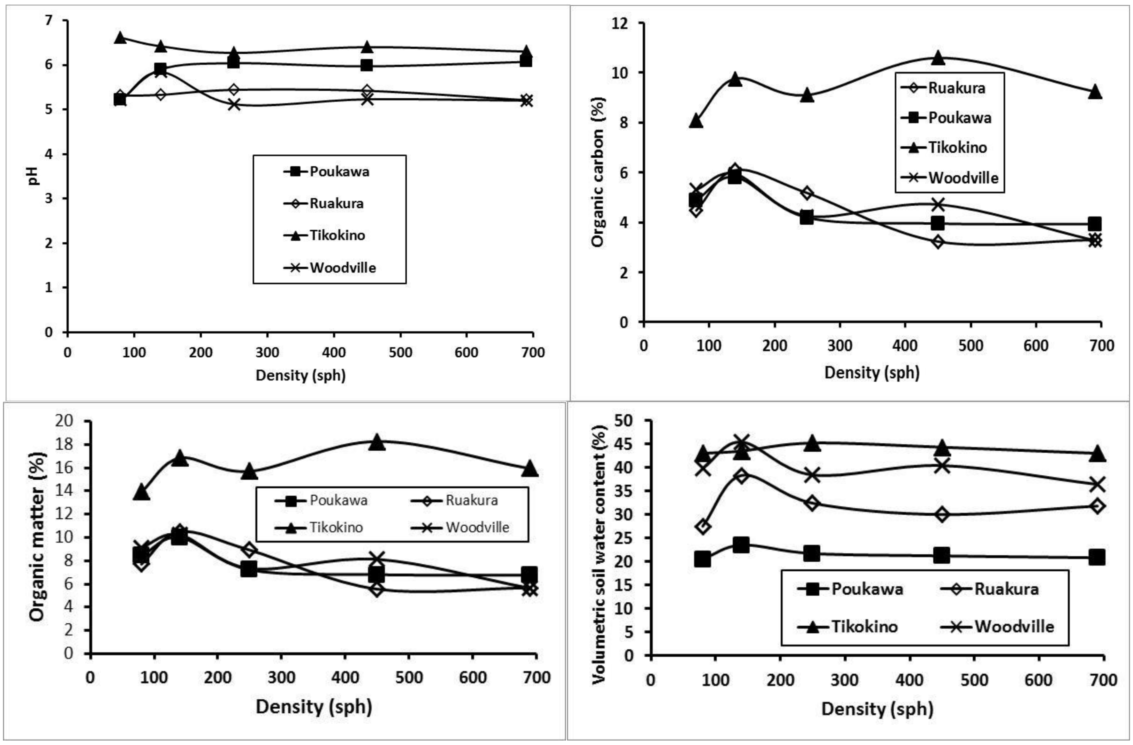


Figure 16. Soil pH, organic carbon and organic matter contents (%), and volumetric soil water content (%) at 0-75 mm depth beneath trees of poplar at Tikokino and Woodville and alder at Poukawa and Ruakura at five densities in Nelder radial planting designs in October 2012.

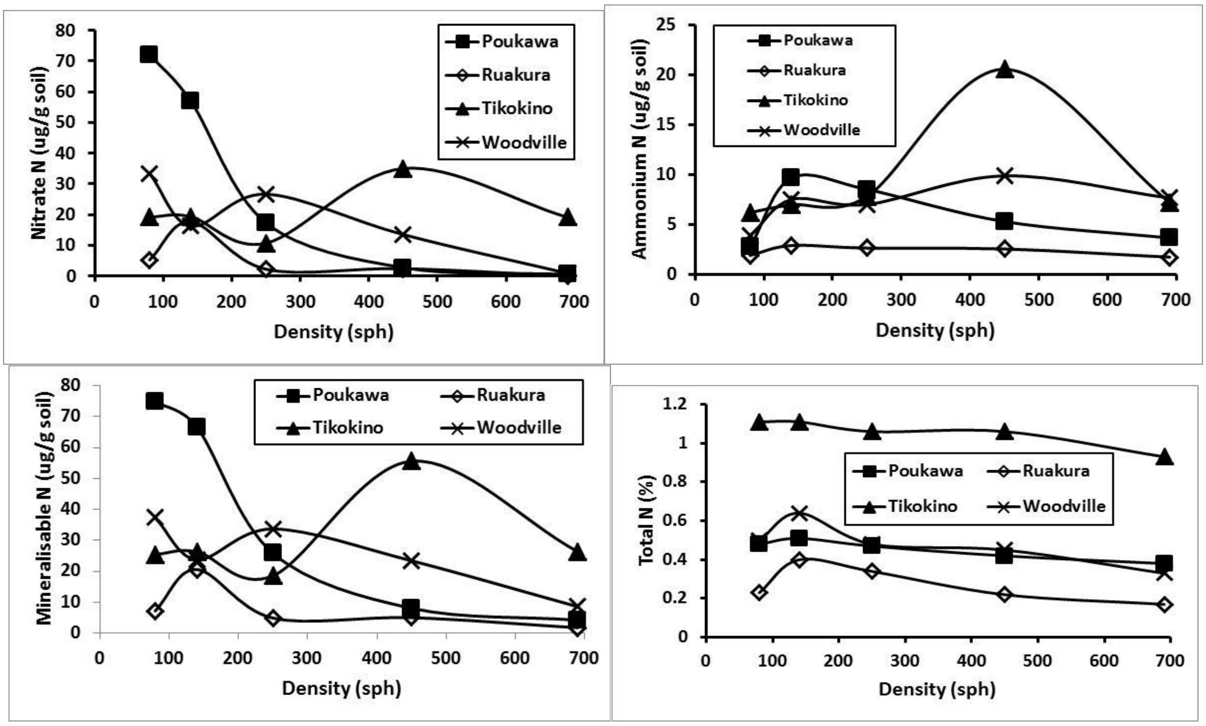


Figure 17. Soil nitrate-N, ammonium-N and mineralisable-N content (ug/g soil), and total N concentration (%) at 0-75 mm depth beneath trees of poplar at Tikokino and Woodville and alder at Poukawa and Ruakura at five densities in Nelder radial planting designs in October 2012.

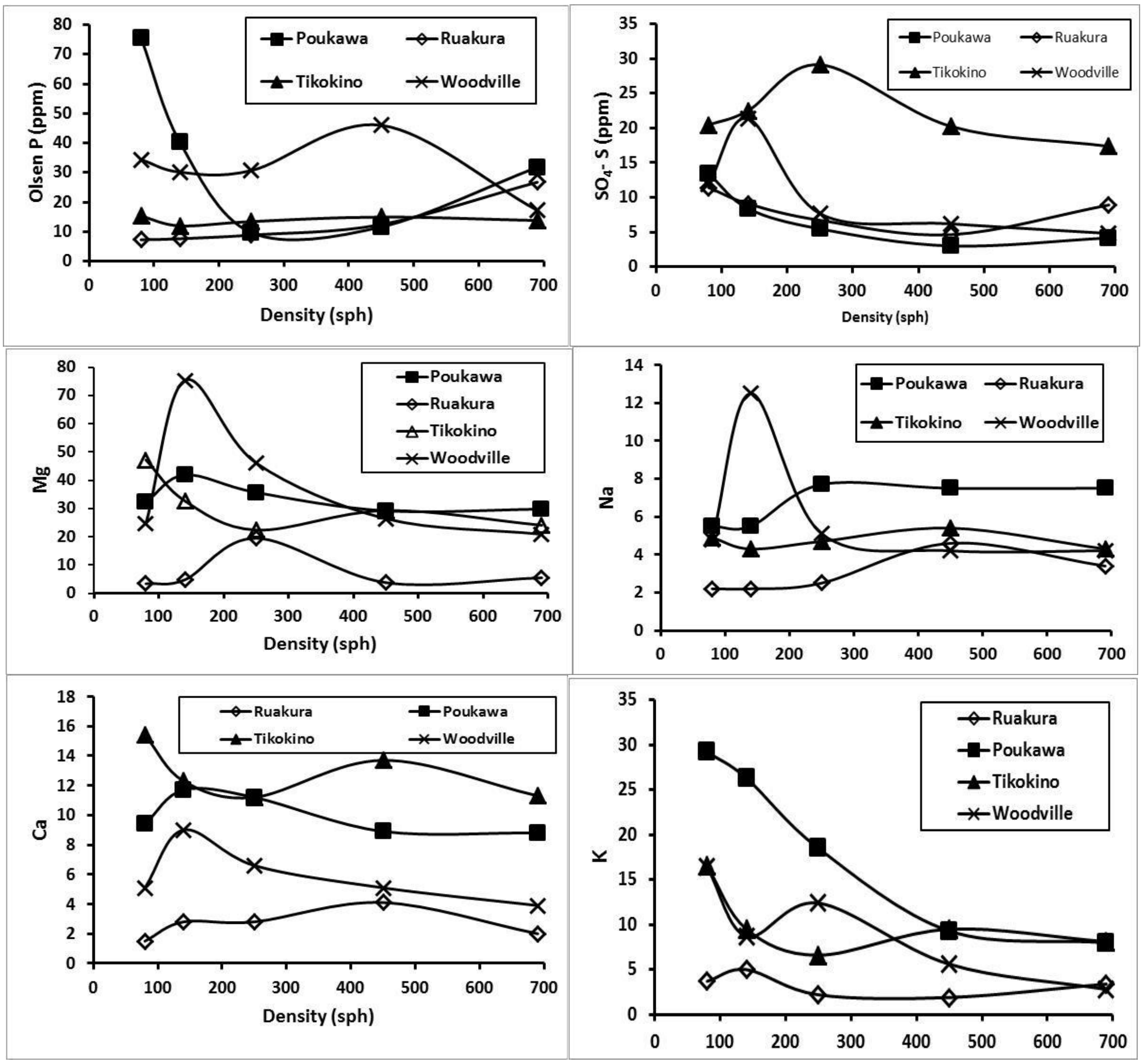


Figure 18. Olsen P (ppm), SO_4-S (ppm) and cations of Mg, Na, Ca and K (Quick-test units) at 0-75 mm depth beneath trees of poplar at Tikokino and Woodville and alder at Poukawa and Ruakura at five densities in Nelder radial planting designs in October 2012.

Tree density had a moderate to pronounced effect at one or more sites on exchangeable cations (Ca, K, Mg and Na), Olsen P, SO_4-S (Figure 18) and concentrations of mineralisable-nitrogen (N), ammonium-N and nitrate-N (Figure 17). This was most evident at Poukawa where soils at low tree density (< 200 sph) had greater values than those at medium to high densities (> 400 sph) for Olsen P (40-75 vs. 12-32 ppm), K (26-29 vs. 8 ppm), mineralisable N (67-75 vs. 4-8 ppm) and nitrate-N (57-72 vs. 1-3 ppm) (Figures 17 and 18). At Tikokino, higher values of mineralisable N, ammonium-N and nitrate-N were found at 450 sph than at the other densities, and at Woodville, levels of Mg and Na were higher at 140 sph than at the other densities.

DBH at each site ranged from 28.6 to 43.3 cm at Tikokino, 28.1 to 37.4 cm at Woodville, 11.8 to 28.6 cm at Ruakura, and 17.8 to 27.7 cm at Poukawa (Figure 19). At all sites, there was a trend of decreasing DBH as tree density increased, except at Poukawa, where no obvious trend was apparent.

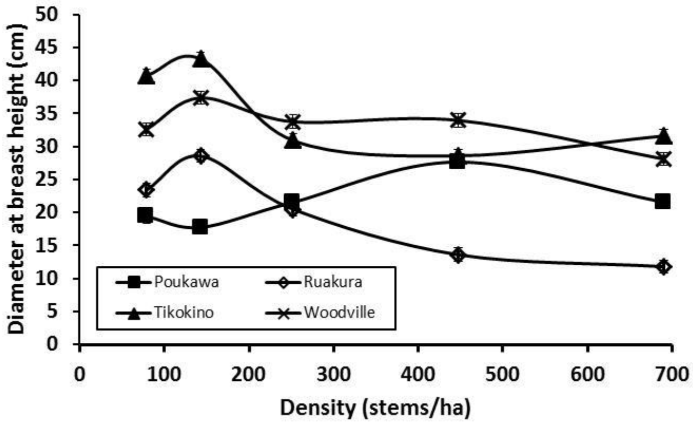


Figure 19. Mean DBH (cm) of trees of poplar at Tikokino and Woodville and alder at Poukawa and Ruakura at five densities in October 2012. Capped vertical bars represent average standard error of mean (*n*=4) at each site.

4.2.2 Main sampling

4.2.2.1 DBH

There was a steady decrease in DBH with increasing density at Tikokino ranging from 47.3 cm at Low density to 26.1 cm at High density (Figure 20). At Poukawa, DBH was approximately constant over the density range, particularly from Low to Medium-high (20-23 cm). More variation in DBH between densities occurred at Ruakura (20.0-27.5 cm) and Woodville (19.9-30.4 cm).

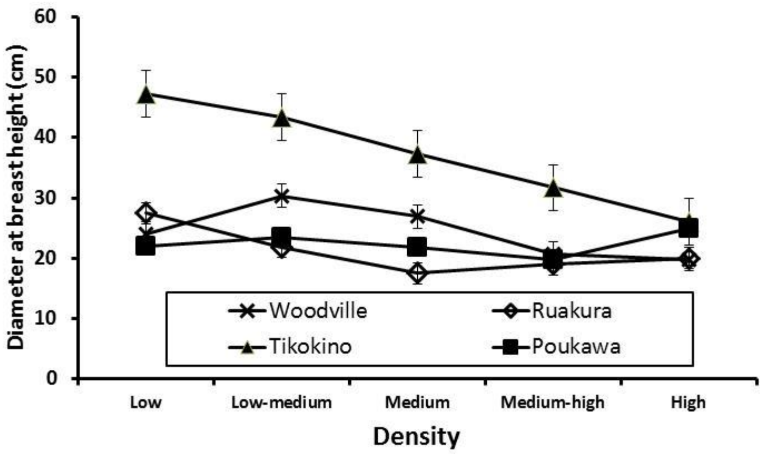


Figure 20. Mean DBH (cm) of trees of poplar at Tikokino and Woodville and alder at Poukawa and Ruakura at five densities in November/December 2012. Refer text for quantification of density categories. Capped vertical bars represent average standard error of mean (*n*=8) at each site.

4.2.2.2 Root mass density

At all sites mean RMD was 3-7 fold greater in TP than Open systems, except at Ruakura, where means in each system did not vary significantly from each other (Table 3). There was a dramatic reduction in RMD with increasing depth at Poukawa, Tikokino and Woodville. At Poukawa for example, RMD declined 97% between 0-75 mm and 600-1000 mm depths and at Woodville the decrease was 96% over the same depth range. An interaction between system and depth was detected only for RMD at Ruakura and was because RMD in the TP system was approximately constant (0.21-0.35 mg/cm^3) across depths, whereas in Open, RMD declined from 3.16 mg/cm^3 at 0-75 mm depth to 0.01 mg/cm^3 at 600-1000 mm depth.

Table 3. Mean root mass density (mg/cm^3) in tree-pasture and open pasture systems at four sites to 1000 mm depth. Means are back transformed from logarithms.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
System					
Pasture	15	0.11b[3]	0.16	0.33b	0.36b
Tree-pasture	100	0.79a	0.29	0.80a	1.23a
Prob.[2]		<0.01	0.23	0.01	<0.01
Depth (mm)					
0-75	23	2.41a	0.47	1.56a	5.37a
75-150	23	1.46ab	0.30	1.05a	2.03b
150-300	23	0.78bc	0.20	0.89a	1.05bc
300-600	23	0.37c	0.28	0.47b	0.52c
600-1000	23	0.08d	0.19	0.27b	0.21d
Prob.		<0.01	0.22	<0.01	<0.01
System x depth					
Prob.		0.29	<0.01	0.40	0.36

[1]sample size; [2]probability of F-test; [3]within columns and categories, figures with different letters are significantly different at 5% level.

Poukawa was the only site where RMD at each tree density was significantly greater than in Open (Table 4). At each of the other sites, mean RMD at many densities was greater than in Open, but no overall differences were detected. At all sites, RMD declined with increasing depth. A depth x density interaction at Ruakura was mainly because RMD at 0-75 mm depth was greater in Open (3.08 mg/cm^3) and Low (1.61 mg/cm^3) densities than at other densities (0.11-0.57 mg/cm^3), in contrast to RMD at 600-1000 mm depth, which was lower in Open (0.01 mg/cm^3) than at any tree density (0.06-0.93 mg/cm^3).

Mean RMD at Woodville was greater than at the other sites but at each site, tree density had no significant effect on RMD (Table 5). At all sites, locations near trees (1 m) had 0.3-2.7-fold greater RMD than at Centre locations. Shallow soil depths had significantly greater RMD than deeper in the profile (Table 5), except at Ruakura where RMD was not affected by soil depth. Poukawa was the only site where interactions between main effects for RMD were not found. At Ruakura, an interaction occurred between depth and density ($P<0.01$), predominantly because of relatively large variation in RMD with depth at Low-medium and High densities, whereas at the other densities, RMD was less variable across depths (not presented). At Tikokino, a depth x location x density interaction ($P = 0.013$) was found, mainly because RMD at 1 m was equal or greater than at Centre location at all depths except at 0-75 mm and 75-150 mm where Centre was greater than 1 m at Low-medium (0-75 mm depth) and Medium (75-150 mm depth) densities (not presented). At Woodville, a location x density interaction ($P = 0.031$) was because RMD at 1 m was greater than at Centre location at Low (5.4 vs. 0.4 mg/cm^3) and Low-medium (2.8 vs. 0.4 mg/cm^3) densities, whereas at the other densities, there was no significant effect of location on RMD.

Table 4. Mean root mass density (mg/cm^3) in tree-pasture systems comprising trees at five densities (sampled at centres of tree groups) and in open pasture at four sites to 1000 mm depth. Means are backtransformed from logarithms.

	n[1]	**Poukawa**	**Ruakura**	**Tikokino**	**Woodville**
Density					
0 (pasture)	15	0.11b[4]	0.16	0.33	0.37
Low[2]	10	0.61a	0.24	0.54	0.36
Low-medium	10	0.48a	0.13	0.51	0.45
Medium	10	0.37a	0.23	0.90	1.06
Medium-high	10	0.67a	0.28	0.81	1.03
High	10	0.27a	0.21	0.51	0.67
Prob.[3]		<0.01	0.74	0.07	0.20
Depth (mm)					
0-75	13	1.84a	0.67a	1.47a	2.29a
75-150	13	0.55b	0.27a	1.20a	0.99ab
150-300	13	0.35bc	0.11b	0.46b	0.81b
300-600	13	0.18c	0.14b	0.30bc	0.26c
600-1000	13	0.06d	0.11b	0.20c	0.12c
Prob.		<0.01	<0.01	<0.01	<0.01
Depth x density					
Prob.		0.44	0.01	0.17	0.97

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]within columns and categories, figures with different letters are significantly different at 5% level.

4.2.2.3 Bulk density

The four sites could be grouped in pairs based on their bulk density. At all depths, Poukawa and Woodville had similar bulk density and values were up to twice those at Ruakura and Tikokino (Figure 21). At Poukawa and Woodville, there was a gradual increase in bulk density with depth, whereas this trend was less pronounced at the other two sites.

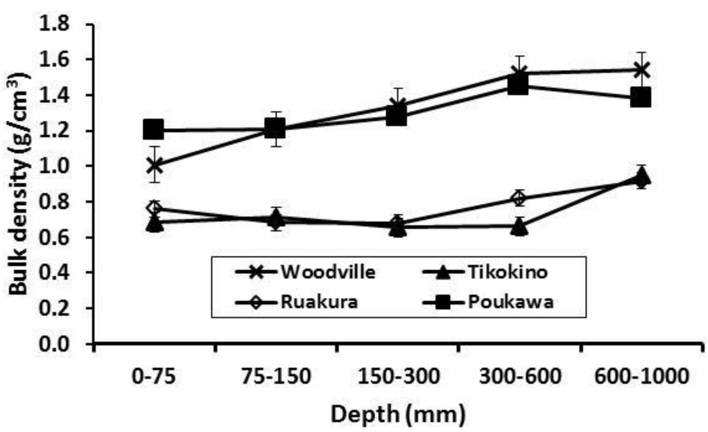


Figure 21. Mean soil bulk density (g/cm^3) at four sites in November/December 2012. Capped vertical bars represent average standard error of mean (*n*=23) at each site.

Table 5. Mean root mass density (mg/cm^3) at two locations within five tree densities at four sites to 1000 mm depth. Means are backtransformed from logarithms except for those for Ruakura which are backtransformed from square roots.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
Density					
Low[2]	20	0.90	0.30	0.63	1.38
Low-medium	20	0.85	0.59	0.77	1.11
Medium	20	0.89	0.55	0.84	1.54
Medium-high	20	1.05	0.56	1.12	1.23
High	20	0.39	0.59	0.69	0.91
Prob.[3]		0.29	0.40	0.36	0.73
Location[4]					
Centre	50	0.44b[5]	1.79b	0.63b	0.63b
1 m	50	1.35a	2.33a	1.01a	2.32a
Prob.		<0.01	<0.01	0.01	<0.01
Depth					
0-75	20	2.69a	0.60	1.61a	6.36a
75-150	20	2.01a	0.33	1.09a	2.25b
150-300	20	1.08ab	0.56	1.13a	1.05bc
300-600	20	0.53b	0.75	0.51b	0.60cd
600-1000	20	0.09c	0.37	0.31b	0.29d
Prob.		<0.01	0.16	<0.01	<0.01

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]Centre = within groups of four trees at each density, 1 m = distance from a tree in each group; [5]within columns and categories, figures with different letters are significantly different at 5% level.

4.2.2.4 Soil C concentration

The highest mean soil C concentrations were found at Ruakura and Tikokino and they were often at least 2 or 3-fold greater than at Poukawa and Woodville, which had similar values (Table 6). At Tikokino, Open pasture had 11% higher mean C concentration than the TP system, but at the other sites, no significant differences in concentration were found between the systems. At all sites, C concentration decreased with increasing depth ($P<0.01$). At Poukawa, a system x depth interaction was detected because at 300-600 mm depth, soil C concentration in Open pasture was greater than in the TP system (1.9% vs. 1.1%), whereas at 600-1000 mm depth, concentration in the TP system exceeded that in the Open (0.8% vs. 0.4%). A system x depth interaction at Ruakura was mainly because C concentration was greater in Open than TP systems at 0-75 (14.9% vs. 11.2%) and 75-150 (11.2% vs. 8.6%) mm depths in contrast to deeper in the soil profiles where C concentration in each system did not vary significantly (not presented).

Table 6. Mean soil carbon concentration (%) in tree-pasture and open pasture systems at four sites to 1000 mm depth. Means for Poukawa and Woodville are backtransformed from square roots.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
System					
Pasture	15	1.8	7.9	6.9a[3]	2.0
Tree-pasture	100	1.9	7.2	6.2b	1.9
Prob.[2]		0.41	0.34	0.01	0.73
Depth (mm)					
0-75	23	4.4a	11.7a	11.0a	5.3a
75-150	23	2.6b	8.9b	8.6b	3.0b
150-300	23	1.4c	7.8b	5.8c	1.7c
300-600	23	1.2c	5.7c	4.1d	1.0d
600-1000	23	0.8 d	2.3d	2.0e	0.4e
Prob.		<0.01	<0.01	<0.01	<0.01
System x depth					
Prob.		<0.01	0.01	0.39	0.05

[1]sample size; [2]probability of F-test; [3]within columns and categories, figures with different letters are significantly different at 5% level.

At each site, the five densities of trees and Open pasture had similar soil C concentrations except at Poukawa where soil in the Medium-high density had greater concentration than soil in Open and Low, Low-medium and Medium tree densities (Table 7). A prominent feature at all sites was a decline in C concentration with increasing soil depth. An interaction between density and depth was only detected at Poukawa and was mainly because concentration was approximately stable across tree densities and Open pasture at 75-150 (2.1-2.8%) and 150-300 (1.2-1.5%) mm depths whereas at other depths, greater variation occurred. For example, at 0-75 mm depth, concentration ranged from 3.7% in Medium density to 5.0% in Medium-high density, and at 300-600 mm depth, concentration varied from 0.6% at Low and Low-medium densities to 1.9% in the Open.

Table 7. Mean soil carbon concentration (%) in tree-pasture systems comprising trees at five densities (sampled at centres of tree groups) and in open pasture at four sites to 1000 mm depth. Means for Tikokino are backtransformed from square roots.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
Density					
0 (pasture)	15	1.9bc[4]	8.0	6.5	2.2
Low[2]	10	1.7d	8.4	5.9	2.0
Low-medium	10	1.8cd	6.9	5.8	1.8
Medium	10	1.7d	7.2	5.6	2.2
Medium-high	10	2.4a	6.0	5.4	2.4
High	10	2.1ab	5.8	5.3	2.5
Prob.[3]		<0.01	0.08	0.14	0.13
Depth (mm)					

0-75	13	4.2a	11.7a	10.8a	4.7a
75-150	13	2.5b	9.0b	8.7b	2.8b
150-300	13	1.3c	7.3b	5.8c	1.8c
300-600	13	1.1c	5.3c	3.8d	1.2d
600-1000	13	0.6d	2.2d	1.9e	0.4e
Prob.		<0.01	<0.01	<0.01	<0.01
Depth x density					
Prob.		<0.01	0.20	0.99	0.29

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]within columns and categories, figures with different letters are significantly different at 5% level.

Within tree densities, C concentration in High density at Poukawa was 20% greater than at the three lowest densities, whereas at Tikokino, the High density had 12% less concentration than

Table 8. Mean soil carbon concentration (%) at two locations within five tree densities at four sites to 1000 mm depth.

	n[1]	**Poukawa**	**Ruakura**	**Tikokino**	**Woodville**
Density					
Low[2]	20	2.0b[5]	8.0	6.6a	2.4
Low-medium	20	2.1b	7.1	6.4ab	2.1
Medium	20	2.0b	7.7	6.5ab	2.3
Medium-high	20	2.2ab	6.4	6.0bc	2.6
High	20	2.4a	6.2	5.7c	2.2
Prob.[3]		0.01	0.11	<0.01	0.11
Location[4]					
Centre	50	1.9b	6.7	6.2	2.2b
1 m	50	2.3a	7.5	6.3	2.5a
Prob.		<0.01	0.14	0.27	0.01
Depth (mm)					
0.75	20	4.6a	11.1a	11.0a	5.6a
75-150	20	2.7b	8.5b	8.6b	3.1b
150-300	20	1.4c	7.5bc	5.6c	1.7c
300-600	20	1.1d	5.9c	4.1d	1.0d
600-1000	20	0.9e	2.4d	1.9e	0.4e
Prob.		<0.01	<0.01	<0.01	<0.01

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]Centre = within groups of four trees at each density, 1 m = distance from a tree in each group; [5]within columns and categories, figures with different letters are significantly different at 5% level.

the average of the Low, Low-medium and Medium densities (Table 8). No significant differences in concentration were found between densities at Ruakura and Woodville. Around trees, C concentration at 1 m was 21% (Poukawa) or 14% (Woodville) greater than at Centre locations, and although results for Ruakura and Tikokino followed a similar trend, differences were not significant. Carbon concentrations decreased with increasing soil depth at all sites (Table 8). Interactions between main effects occurred only at Poukawa and Woodville, comprising density x location at Poukawa ($P<0.01$) and Woodville ($P=0.01$), depth x density at Poukawa ($P<0.01$) and location x depth ($P<0.01$) at Woodville. The density x location interaction at Poukawa was because C concentration at 1 m was greater than Centre at all densities (2.3-2.6% vs. 1.7-2.1%) except at Medium-high density where concentration at Centre exceeded that at 1 m (2.4% vs. 2.0%). The depth x density interaction at the same site mainly arose from variation in C concentration between the three deepest depths in Low (0.5-1.4%) and Low-medium (0.5-1.5%) densities and no significant differences in mean concentration in Medium (1.0-1.3%), Medium-high (1.1-1.2%) and High (1.3-1.6%) densities. C concentration at 75-150 mm depth was similar across the density range (2.5-2.8%) whereas it varied at 0-75 mm depth from 4.2% at Medium density to 5.0% at Low density. Concentrations increased steadily with increasing tree density at 300-600 (0.7% (Low) to 1.8% (High)) and 600-1000 mm (0.5% to 1.3%) depths.

At Woodville, the density x location interaction was because C concentration at 1 m exceeded that at Centre at Low density (2.9% vs. 1.9%) in contrast to all other densities, where no significant differences between locations were detected. The location x depth interaction at Woodville was explained by mean C concentration at 1 m being greater than Centre at 0-75 (6.3% vs. 4.9%) and 75-150 (3.3% vs. 2.8%) mm depths whereas values at each location did not vary significantly deeper in soil profiles.

4.2.2.5 Soil C mass

Mean C mass was similar at Ruakura and Tikokino (60-76 t C/ha) and was about twice that calculated at Poukawa and Woodville (Table 9). Mass in Open pasture exceeded that in the TP system by 27% at Tikokino and Woodville in contrast to Poukawa and Ruakura where no significant differences between systems were found. The effect of depth on C mass varied between sites and there was no distinct increase or decrease in mass with increasing depth. For example, at Poukawa, C mass at 0-75, 300-600, and 600-1000 mm depths was at least 42% greater than at 75-150 and 150-300 mm depths and at Tikokino, C mass at 300-600 and 600-1000 mm depths exceeded that in depth increments within the range 0-300 mm (Table 9). Poukawa was the only site where an interaction between system and depth was found and was because C mass was greater in the Open than in the TP system at 300-600 mm depth (81 vs. 43 t C/ha) whereas the reverse occurred at 600-1000 mm depth with C mass in the TP system exceeding that in the Open (40 vs. 22 t C/ha). At the other depths there was no significant difference between mass in each system.

Density affected C mass at Poukawa and Tikokino but did not significantly influence mass at the other two sites (Table 10). At Poukawa, C mass in Medium-high and High densities was greater than in the three lowest tree densities, and the estimate for Medium-high exceeded that in the Open (44 vs. 35 t C/ha). In contrast, at Tikokino, C mass in the tree densities was less than in the Open, except mass in Low density which was not significantly different from in the Open. At all sites, C mass at 300-600 mm depth was greater than at all other depths, apart from at Tikokino where masses at 300-600 and 600-1000 mm depths were not significantly different. There was a depth x density interaction for C mass at Poukawa mainly because there was no effect of density on C mass at depths of 0-75 (range 33-45 t C/ha), 75-150 (17-26 t C/ha) and 150-300 (21-30 t C/ha) mm whereas there was significant variation at 300-600 (25-81 t C/ha) and 600-1000 (18-65 t C/ha) mm depths.

At Poukawa, High density had greater mean C mass than the other densities, including 48% greater than Low density and 39% greater than Low-medium and Medium densities (Table 11). In contrast, at Woodville, there was less variation between densities with C mass of all densities except Low-medium not significantly different from each other. Carbon mass of Medium and Medium-high densities exceeded that of Low-medium density by 33% and 26%, respectively. At Ruakura and Tikokino, C mass was not affected by tree density. Poukawa was the only site where C mass was influenced by location, with mean at 1 m being 34% greater than at Centre (Table 11). At all sites, C mass varied with depth, although the patterns were different between sites. For example, at Poukawa and Ruakura, C mass at 0-75 mm depth was not significantly different from that at 600-1000 mm depth whereas at Woodville, C mass at 0-75 mm depth was 90% greater than at 600-1000 mm depth (40 vs. 21 t C/ha). Interactions between main effects were only detected at Poukawa (two interactions) and Woodville (one). At Poukawa, a density x depth interaction (P=0.01) was mainly because of the variability in C mass between densities at 300-600 and 600-1000 mm depths compared with at other depths. All densities had similar C masses at 0-75 (37-44 t C/ha), 75-150 (22-25 t C/ha) and 150-300 (23-30 t C/ha) mm depths whereas at 300-600 mm depth, C mass at High (75 t C/ha) and Medium-high (52 t C/ha) densities was greater than at the other densities (30-36 t C/ha). At 600-1000 mm depth, mass was 67 t C/ha at High, 56 t C/ha at Medium-high, 42 t C/ha at Medium, 27 t C/ha at Low-medium and 25 t C/ha at Low. Also at Poukawa, density interacted with location (P<0.01) with C mass at 1 m being 38-58% greater than at Centre at all densities except at Medium-high where mass at Centre exceeded that at 1 m (42 vs. 33 t C/ha). At Woodville, a depth x location interaction (P<0.01) was because at 300-600 mm depth, C mass at Centre was greater than at 1 m (51 vs. 34 t C/ha) whereas at all other depths, mass did not vary significantly between locations and there was a difference of less than 8 t C/ha.

Table 9. Mean soil carbon (C) mass (t C/ha) in tree-pasture and open pasture systems at four sites to 1000 mm depth. Means for all sites are backtransformed from logarithms, except those for Tikokino which are backtransformed from square roots.

	n[1]	**Poukawa**	**Ruakura**	**Tikokino**	**Woodville**
<u>System</u>					
Pasture	15	33	66	76a[3]	38a
Tree-pasture	100	34	72	60b	30b
Prob.[2]		0.78	0.50	<0.01	<0.05
<u>Depth (mm)</u>					
0-75	23	40a	64b	56c	39ab
75-150	23	24b	43c	46d	27c
150-300	23	26b	72b	56c	33b
300-600	23	47a	121a	80a	41a
600-1000	23	37a	74b	73b	21d
Prob.		<0.01	<0.01	<0.01	<0.01
<u>System x depth</u>					
Prob.		0.01	0.16	0.35	0.35

[1]sample size; [2]probability of F-test; [3]within columns and categories, figures with different letters are significantly different at 5% level.

Table 10. Mean soil carbon (C) mass (t C/ha) in tree-pasture systems comprising trees at five densities (sampled at centres of tree groups) and in open pasture at four sites to 1000 mm depth. Means for Poukawa are backtransformed from square roots and data for Ruakura and Tikokino are backtransformed from logarithms.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
Density					
0 (pasture)	15	35b[4]	67	72a	41
Low[2]	10	24c	83	62ab	31
Low-medium	10	25c	70	58b	27
Medium	10	26c	72	56b	41
Medium-high	10	44a	71	54b	32
High	10	38ab	59	54b	37
Prob.[3]		<0.01	0.51	0.04	0.13
Depth (mm)					
0-75	13	38b	63b	55b	36b
75-150	13	22d	44c	46c	26c
150-300	13	25d	68b	56b	36b
300-600	13	46a	116a	76a	55a
600-1000	13	30c	73b	72a	22c
Prob.		<0.01	<0.01	<0.01	<0.01
Depth x density					
Prob.		<0.01	0.57	0.99	0.15

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]within columns and categories, figures with different letters are significantly different at 5% level.

Table 11. Mean soil carbon (C) mass (t C/ha) at two locations within five tree densities at four sites to 1000 mm depth. Means for Poukawa and Ruakura are backtransformed from logarithms and data for Woodville are backtransformed from square roots.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
Density					
Low[2]	20	29c[5]	75	66	30ab
Low-medium	20	31bc	70	63	27b
Medium	20	31bc	73	62	36a
Medium-high	20	37ab	72	60	34a
High	20	43a	65	58	32ab
Prob.[3]		<0.01	0.88	0.31	0.04
Location[4]					
Centre	50	29b	69	60	32

1 m	50	39a	73	63	32
Prob.		<0.01	0.49	0.19	0.92
Depth (mm)					
0-75	20	40a	63b	56c	40a
75-150	20	24b	42c	46d	26b
150-300	20	26b	71b	56c	32b
300-600	20	43a	125a	80a	42a
600-1000	20	40a	78b	71b	21c
Prob.		<0.01	<0.01	<0.01	<0.01

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]Centre = within groups of four trees at each density, 1 m = distance from a tree in each group; [5]within columns and categories, figures with different letters are significantly different at 5% level.

4.2.2.6 Total C mass

Highest mean total mass to a depth of 1 m was estimated at Ruakura and Tikokino of 300-410 t C/ha, which exceeded estimates at Poukawa and Woodville by 100-140 t C/ha (Table 12). Tikokino was the only site where a significant difference ($P<0.01$) between systems was found with Open pasture having 31% greater C mass than the TP system. At Woodville, significance was only $P = 0.08$, but the Open had 23% more C mass than the TP system.

Table 12. Mean total soil carbon (C) mass (t C/ha) in tree-pasture and open pasture systems at four sites to 1000 mm depth, summed over five depths.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
Pasture	3	187	348	396a[3]	203
Tree-pasture	20	192	410	302b	165
Prob.[2]		0.92	0.43	<0.01	0.08

[1]sample size; [2]probability of F-test; [3]within columns, figures with different letters are significantly different at 5% level.

In Open pasture and each tree density (Centre locations) at Poukawa, total C mass in Medium-high density was greater than in other treatments in the order Medium-high > Open > Low, Low-medium, and Medium (Table 13). Total C mass in the High density was not significantly different from that in the Open and Medium-high density. At the three other sites, there was no significant effect of density on mean total C mass.

Table 13. Mean total soil carbon (C) mass (t C/ha) in tree-pasture systems comprising trees at five densities (sampled at centres of tree groups) and in open pasture at four sites to 1000 mm depth, summed over five depths.

	n[1]	Poukawa	Ruakura	Tikokino	Woodville
0 (pasture)	3	187b[4]	351	391	203
Low[2]	2	121c	462	316	154

Low-medium	2	129c	423	295	136
Medium	2	134c	381	284	203
Medium-high	2	229a	403	273	161
High	2	194ab	344	279	182
Prob.[3]		<0.01	0.89	0.09	0.26

[1]sample size; [2]refer to text for quantification of density categories; [3]probability of F-test; [4]within columns, figures with different letters are significantly different at 5% level.

In the analysis comprising the five tree densities and two locations at each site, differences between densities and locations in mean total C mass were non-significant, except at Poukawa where mass 1 m from trees exceeded that at Centre location (222 vs. 161 t C/ha; P=0.01). No interaction between density and location was detected at any site.

4.3 IMPACTS OF SILVOPASTORAL SYSTEMS ON GREENHOUSE GAS EMISSIONS

The Open farm scenario carried the largest amount of breeding ewes; cattle livestock numbers remained equal for all scenarios. The largest carrying capacity of the Open scenario originated from the greater whole-farm annual pasture production compared with the TP scenarios; an extra tonne of DM produced (8656 vs. 7569 kg DM) (Table 14 and Figure 3).

Table 14. Pasture production, stock numbers carried through winter (at 1-Jul), and supplemental feed of the seven farm scenarios tested (Open vs. Tree_ pasture systems). Outputs from Farmax.

	Scenario modelled						
	Open	Trees_0	Trees_10	Trees_30	Trees_50	Trees_I100	Trees_I25
Pasture[1]	8656	7569	7569	7569	7569	7569	7569
Stock, SU/ha	13.4	11.9	11.9	11.9	11.9	12.5	12.1
Ewes	2379	2026	2033	1985	1984	2074	1987
Ewe hoggets	586	502	502	491	489	512	491
MS[2] hoggets	402	342	344	336	335	350	335
Rams	35	29	29	29	29	31	31
Total sheep	3402	2899	2908	2841	2837	2967	2844
1-year bulls	96	96	96	96	96	96	96
2-year bulls	93	93	93	93	93	93	93
Total cattle	189	189	189	189	189	189	189
Swedes, ha	10	10	10	10	10	10	10
N applied[3], ha	73.6	73.6	73.6	73.6	73.6	73.6	73.6

[1]Annual pasture production, kg DM/ha. [2]Mixed mob. [3]N applied at an annual rate of 28 kg N/ha.

Total DMI ranged from 6.98 (Trees_0) to 7.91 t DM/ha (Open) (Table 15). Annual pasture utilisation (calculated as pasture DMI divided by pasture DM production in kg/ha) ranged from 81.1 (Open) to 83.0% (Trees_I100). Feed conversions achieved by the Tree_I100 and Tree_I25 scenarios (22.6 kg DMI/kg meat and fibre) were more efficient than that of the Open scenario (24.2 kg DMI/kg meat and fibre) (Table 15).

Table 15. Performance indicators of the seven farm scenarios tested. (Open vs. Tree_ pasture systems). Outputs from Farmax.

	Scenario modelled						
	Open	Trees_0	Trees_10	Trees_30	Trees_50	Trees_I100	Trees_I25
Intake, t DM/ha							
Pasture	7.55	6.63	6.66	6.64	6.67	6.75	6.71
Supplements[1]	0.36	0.36	0.36	0.36	0.36	0.61[2]	0.44[2]
Total	7.91	6.98	7.02	6.99	7.02	7.36	7.15
Pasture util., %[3]	81.1	81.2	81.7	81.4	81.8	83.0	82.4
FCE[4]	24.2	24.0	23.7	23.4	23.0	22.6	22.6
Species ratio							
Sheep, %	79	76	77	77	77	78	77
Beef, %	21	24	23	23	23	22	23

[1]From fodder crop grown on farm and hay from excess pasture growth. [2]Poplar supplementation (see text for more detail) + described supplements. [3]Pasture utilisation, percent of total amount produced. [4]Feed conversion efficiency, kg DM consumed/kg animal product.

Meat production (net carcass weight) ranged from 224 (Trees_0) to 255 kg/ha (Trees_I100) (Table 16). Similarly, total animal product (meat + fibre) ranged from 271(Trees_0) to 305 kg/ha (Trees_I100). Gross margins ranged from 669 (Trees_0) to 796$/ha (Trees_I100).

Table 16. Animal performance and financial indicators of the seven farm scenarios tested (Open vs. Tree_ pasture systems). Outputs from Farmax.

	Scenario modelled						
	Open	Trees_0	Trees_10	Trees_30	Trees_50	Trees_I100	Trees_I25
Meat, kg/ha	249	224	229	231	237	255	247
Wool, kg/ha	55	47	47	47	47	50	48
Total, kg/ha	304	271	276	278	284	305	295
Gross margin[1]	761	669	686	699	725	796	767

[1]Gross margin, $/ha. Calculated as the difference between total revenue (animal sales minus purchases) and expenses (hay making, forage crop, N expenses, animal health, shearing costs, and interest on capital).

The shelter benefits from ewes having free access to the tree land blocks (scenarios Trees_10, Trees_30 and Trees_50) were captured in reduced lamb losses relative to the Open scenario, which in turn resulted in greater lambing % (135, 141 and 147% vs. 132%) and weaning % (131, 138 and 144% vs. 128%) (Table 17). To a greater extent, the additional intake from tree leaves provided for greater reproductive efficiency; lambing % and weaning % for both scenarios with added DMI from tree leaves (Tree_I100 and Tree_I25) were increased to 154 and 151%, respectively.

Table 17. Reproductive performance of the seven farm scenarios tested (Open vs. Tree_ pasture systems). Outputs from Farmax.

	Scenario modelled						
	Open	Trees_0	Trees_10	Trees_30	Trees_50	Trees_I100	Trees_I25
Ewe pregnancy, %	162	162	162	162	162	177	177
Ewe lambing, %	132	132	135	141	147	154	154
Ewe weaning, %	128	128	131	138	144	151	151
Ewe efficiency index[1]	54.7	54.7	55.8	58.7	61.5	64.5	64.5

[1]Ewe efficiency index = total standardised lamb weaning weight (at 90 days, in kg) per kg ewe mated, expressed as a percentage.

A greater carrying capacity was associated with greater total emissions (4832 vs. 4265 kg CO_2-e/ha for the Open vs. Tree_0 scenarios, respectively) (Table 18); methane emissions accounted for up to 70% of total emissions (Figure 22). Emissions intensity ranged from 14.5 (Trees_I100) to 15.9 CO_2-e/kg meat and fibre (Open); relative to the Open scenario, Trees_I100 achieved a 9% reduction in emissions intensity (Figure 23).

Table 18. Nitrogen losses and greenhouse gas (GHG) emissions for the seven farm scenarios tested (Open vs. Tree_ pasture systems). Output from Overseer

	Scenario modelled						
	Open	Trees_0	Trees_10	Trees_30	Trees_50	Trees_I100	Trees_I25
Nitrogen, kg N/ha							
Applied	5.9	5.9	5.9	5.9	5.9	5.9	5.9
Leached	13.1	12.0	11.8	11.7	11.7	12.0	11.8
N_2O emissions	2.6	2.4	2.4	2.3	2.3	2.4	2.4
GHG emissions, kg CO_2-e/ha							
Methane (CH_4)	3379	2933	2948	2923	2939	3086	2987
Nitrous oxide (N_2O)	1223	1124	1101	1092	1094	1127	1103
Carbon dioxide	230	208	207	207	209	207	211
Total emissions	4832	4265	4256	4222	4242	4420	4301
GHG emissions intensity, kg CO_2-e/kg of meat and fibre							
	15.9	15.7	15.4	15.2	14.9	14.5	14.6

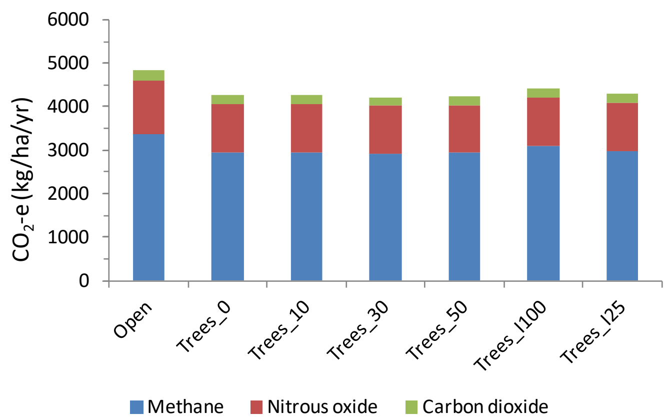


Figure 22. Greenhouse gas (GHG) emissions (methane, nitrous oxide, carbon dioxide) for the seven farm scenarios simulated (Open vs. Tree_ pasture systems). Outputs from Overseer.

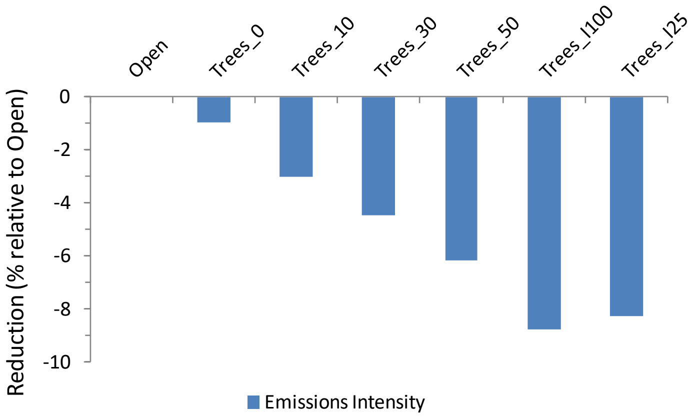


Figure 23. Reduction in greenhouse gas (GHG) emissions intensity (kg CO_2-e/kg of meat and fibre) from simulated tree-pasture farming systems relative to an Open pasture sheep and beef farming system in Manawatu. Outputs from Overseer.

5. Discussion

5.1 BACKGROUND DATA

Accessing and collating early trial data at each site were important to provide a reference for future measurements, enabling quantification of any temporal changes in attributes and potential interactions with density. The negligible effect of tree density on a range of attributes across the four sites was likely because measurements were conducted when the trees were young, usually aged less than four years. It gives confidence that any differences that might emerge at later samplings are a result of the current rather than previous practices. A notable exception was the decrease in percent grass in pastures with increasing density at all sites except at Woodville where no effect of density was detected. The response of percent grass to density at three sites was probably due to altered light quantity and quality (Dodd *et al.* 2005) and ground surface temperature patterns arising from tree canopy development, because no significant effects of density on soil water content were detected and few effects on soil nutrient attributes were found at specific times. Shading has significant effects on understorey grass morphology and growth processes in tree-pasture systems and responses vary with species (Lin *et al.* 1998; Devkota *et al.* 2000; Devkota *et al.* 2009). Older deciduous trees at various densities or with closed canopies influence a number of attributes including pasture production and botanical composition, root number and cross sectional area, soil pH and soil nutrient contents (Guevara-Escobar *et al.* 1997; Wall *et al.* 1997; Guevara-Escobar 1999; Douglas *et al.* 2001; Guevara-Escobar *et al.* 2002; Douglas *et al.* 2006b; Douglas *et al.* 2006a; Wall 2006; Wall *et al.* 2006; Guevara-Escobar *et al.* 2007; Douglas *et al.* 2010) and it is therefore likely that the effects of tree density would become more apparent as the trees at the four sites aged.

At some sites a few attributes varied between Open and TP systems. For example at Poukawa, Olsen P, SO_4-S and K concentration were distinctly greater in Open than in TP systems in contrast to Na concentration which was relatively low in Open. At Ruakura, total N concentration and Olsen P were often higher in Open than TP areas, whereas bulk density and SO_4-S in Open were frequently similar to or less than at positions around trees. No measurements before planting were conducted at the sites so it is not possible to determine if these differences were because of inherent site variability. The sites were grazed by livestock although details such as stock class, stock number, and grazing frequency and duration are unavailable. Spaced trees change livestock grazing and other behaviours (Devkota *et al.* 2009; Betteridge *et al.* 2012) and potentially patterns of defecation, urination, and trampling. In the

Nelder radial planting design at each site, the TP and Open systems were in the same paddock and it is possible that grazing behaviour resulted in different patterns of nutrient cycling and soil compaction in Open and adjacent TP areas. This requires clarification.

All soil samples were collected at shallow depths in profiles, mostly 0-75 mm, except those for nitrate-N, ammonium-N and mineralisable-N, which were to 300 mm depth, and VSWC and bulk density at Poukawa which were at 0-300 mm depth. Sampling of all attributes to at least 300 mm depth rather than to 75 mm depth would have been more appropriate for sites with young trees to better reflect below-ground effects from activity of their roots, which typically extend deeper than 75 mm. Near Woodville, young (5-10 years) poplar trees had limited root development on slope angles of 5-15^{o} (McIvor *et al.* 2008; Douglas *et al.* 2010) with greater than 70% of their roots (all diameter classes) in the top 300 mm of soil profiles (Douglas *et al.* 2010). On flat land, recent excavations of entire root systems of poplars aged up to 3 years, established from cuttings, stakes and poles, found greater lateral than vertical root development in a surficial soil layer (0-500 mm depth) than at greater soil depths (Douglas and McIvor, unpubl.), suggesting that deeper sampling in soil profiles was not essential.

Two distinct groups of sites were apparent in the trial series, based on a number of variables. These included pasture production, with average annual production at Ruakura and Woodville approaching 16 t DM/ha, whereas at Tikokino and Poukawa, pasture production averaged closer to 10 t DM/ha, typical of the summer-dry environment in Central Hawke's Bay. The similarity in production between Tikokino (poplar) and Poukawa (alder), and between Woodville (poplar) and Ruakura (alder), suggested that within each group, it would be appropriate to use differences between tree species as an important reason for any differences in measured soil attributes between sites. In comparison to poplars, alders are N-fixing tree species. Confounding with geo-climatic factors would still exist but would be less critical than in other comparisons such as those between attributes measured in poplar stands at Tikokino and alder stands at Ruakura. The Ruakura and Tikokino sites have soils of volcanic origin, with deep, free-draining profiles (Ruakura site also contains stones), in comparison to soils at Poukawa and Woodville, which are derived from sedimentary materials, and are poorly drained because of the weakly developed structured B and C soil horizons. The landscape position of the Woodville site, being almost a valley floor, would also result in a high water table during winter months. To the contrast of geo-climate and associated primary production levels between sites, and the contrast between tree species, must be added the contrasts because of soil type, which includes anion storage capacity and drainage characteristics, which influence both plant growth and C cycling and accumulation in soils.

The Woodville site provided particularly relevant background data for the November/December 2012 field study because it was the only site where organic C (and organic matter) concentration was determined, albeit at only 0-75 mm depth. In November 2000, about four years after tree planting, organic C concentration averaged 5.1% across all tree densities. It was not significantly affected by density, probably because trees were young with consequently negligible effects on nutrient cycling stocks and processes in the existing pasture. It does provide some confidence that any differences found in the current study are because of current rather than previous practice or within-site variation.

5.2 PRELIMINARY FIELD STUDY - IMPACTS OF TREES ON SOIL NUTRIENTS

The effect of tree density on a range of attributes at one or more sites in October 2012 contrasted with the minimal effects of density found within the first five years after planting. In October 2012, trees were aged 14 years (Poukawa and Ruakura) and16 years (Tikokino and Woodville), were well established with canopies often of at least 10 m diameter, and were significant components in the agro-ecosystems at each site. Changes in soil chemical and physical attributes and other characteristics have been found in the presence of intermediate aged and older trees of *Populus* and *Alnus* spp., usually in forests, short-rotation coppices and tree-crop systems (Lavery *et al.* 2004; Moscatelli *et al.* 2005; Kahle *et al.* 2007; Sharma *et al.* 2009; Uri *et al.* 2011) but rarely in tree-pasture systems (Guevara-Escobar *et al.* 2002; Douglas *et al.* 2006b). However most of these studies have been restricted to comparisons at one or two unspecified densities, rather than the wide range explored presently.

The higher organic C concentration at Tikokino (range 8.1-10.6%) than at the other sites (3.9-6.1%) likely reflected differences between the sites in the parent material of the soils, along with any differences in the quantity and quality of inputs of tree leaf, pasture litter and fine root tissues, and the rate and extent of their decomposition. The pronounced presence of volcanic ash in the soil at Tikokino would result in more stable organic matter accumulation in the soil. The soil there was porous and easy to sample through coring and digging with a bulk density (0-75 mm depth in November/December 2012) in TP areas of 0.69 g/cm^3. Ruakura also had a low bulk density (0.78 g/cm^3), characteristic of soils with good structure from the stable aggregates formed from the association of the organic matter with the allophane in the volcanic ash. At Tikokino and Ruakura, there would be little resistance to root growth. The association of higher soil C concentration with lower bulk density is well established in forestry ecosystems (Périé and Ouimet 2008). The Tikokino site was unique among the four sites in having a uniform, healthy pasture cover throughout the Nelder design whereas at the other sites, particularly Ruakura and Poukawa, a number of the high density areas had reduced pasture cover or even bare ground. It is not clear how this variation in understorey vegetative cover may have impacted on the observed results.

In comparison to the low bulk density at Tikokino and Ruakura, and high C concentration at Tikokino, the reverse was true at Woodville and Poukawa. The mean bulk densities of 1.00 mg/m^3 at Woodville and 1.19 mg/m^3 at Poukawa (Figure 21) are approaching densities that create resistance to root penetration. Coupled with the fact that both these soils are weakly developed and structured, with increasing bulk density with depth (e.g. at Woodville 1.00 g/cm^3 at 0-75 mm to 1.54 g/cm^3 at 600-1000 mm), imperfectly drained and winter wet, with seasonal water tables up into the B horizons compounded by the low landscape position of the Woodville site contributing to winter wetness, these two sites present more challenges to plant growth.

Carbon concentration at Woodville averaged 4.7% (range 3.3-5.3%) in the 0-75 mm soil depth. This is slightly less than that found at the same site in November 2000 (average 5.1%; range 4.6-5.9%). Estimates were more variable between densities in October 2012 than in November 2000, maybe reflecting the increasing influence of the tree, with the slight trend of decreasing C concentration as tree density increased. At both times, soil was sampled to 75 mm depth but from different locations within the radial design, being at different positions along a ray/row in October 2012, and at the centre of groups of trees at the earlier assessment. Despite the spatial variation in sampling, comparison between the two times showed that there had been a slight decrease if anything in C concentration during the intervening 12 years. On the one hand, the greater fine root presence at higher tree densities (Douglas *et al.* 2010) and relatively high leaf litter inputs (Guevara-Escobar *et al.* 2002) at higher densities could have enhanced soil C inputs, but other factors such as livestock grazing, effect of pasture-leaf litter balance on decomposition rates, tree root effects on physical soil characteristics and enhanced C mineralisation rates, and abiotic factors such as redistribution of leaf inputs through wind dispersal (Cortez 1998; Devkota *et al.* 2009; Edmonds and Tuttle 2010; Rubino *et al.* 2010; Mao and Zeng 2012), could have reduced any effects of tree density.

The ability of alders to enhance soil N status has been shown overseas (Lavery *et al.* 2004; Sharma *et al.* 2009; Uri *et al.* 2011; Peichl *et al.* 2012) and the relatively high levels of nitrate-N and anaerobically mineralisable-N at low densities (< 200 sph) at Poukawa, and ammonium-N levels of 5-10 ug/g soil at the same site, support this. In contrast to Poukawa, levels of inorganic N at Ruakura were negligible and not affected by tree density. Differences in inorganic N levels between the sites may be explained by a number of biotic and abiotic factors (Knoepp and Vose 2007; Curtin *et al.* 2012; Giles *et al.* 2012; Auyeung *et al.* 2013) but it is suggested that key factors were likely higher soil temperatures and lower rainfall and associated nitrate-N leaching potential at the summer-dry Poukawa site. In October 2012 this site had the lowest VSWC across all densities of approximately 20% compared with mostly 30% or higher at Ruakura. It is possible that the effect of tree density on nitrate-N and mineralisable-N at Poukawa was partly in response to shading because tree canopies did not intermesh until above 400 sph. Lower inorganic N in the TP system at Ruakura than at Poukawa was mimicked in the results for total N concentration where soil at all tree densities at Ruakura was about 0.2% units less than at Poukawa. Across all sites, the results for total N concentration at Tikokino reinforced the findings observed for organic C concentration in showing the relatively high soil quality of this site.

The evidence for an effect of tree density on Olsen P and K concentration at Poukawa was strengthened by the data-points for Olsen P (2 points) and K (3 points) at low densities exceeding those at higher densities. This partly compensated for the lack of replication (n=1) of soil sampled at each density. Olsen P values at densities < 200 sph at Poukawa exceeded 40 ppm which is greater than target soil test levels recommended for near maximum pasture production on sheep and beef farms (Morton and Roberts 2009), whereas values at 250 and 450 sph (approximately 10 ppm) indicated potential phosphate deficiency and requirement for fertiliser. A value of 30 ppm at high density (700 sph) was within the range recommended for near maximum pasture production (Morton and Roberts 2009). Despite K concentration test values at 250 sph or less far exceeding levels recommended to sustain near maximum pasture production, those at higher tree densities were still within the range recommended. The relatively high concentrations of Olsen P and K at low tree densities may be because of differences in grazing behaviours of livestock. It was observed at the time of sampling that livestock (cattle) preferred grazing at low tree densities (beneath shade of individual trees and in open areas between trees) to beneath trees at higher densities where there was maximum shade because of closed canopies. Hence there were potentially more defecation and urination events at low than high densities, resulting in differential nutrient deposition (Watkin and Clements 1978; Haynes and Williams 1993; Kemp *et al.* 1999).

5.3 MAIN FIELD STUDY - IMPACTS OF TREES ON SOIL CARBON

The negative relationship between diameter growth and tree density found at Tikokino supports findings for stands of certain species of poplar (Fang *et al.* 1999; Benomar *et al.* 2012) and species of other genera (Burner *et al.* 2011; Chaturvedi *et al.* 2011; Prasad *et al.* 2011) at a range of sites. However responses of DBH to tree density for poplar are not ubiquitous with for example mean DBH of a clone of hybrid poplar (*Populus balsamifera* x *P. trichocarpa*) at three densities not differing significantly after six growing seasons (Benomar *et al.* 2012). At the other sites, tree density had negligible (Ruakura, Woodville) or no (Poukawa) effect on DBH. The poplar clone in the radial design at Woodville was the same as that at Tikokino so that only non-genetic factors could explain the different responses between the sites. Poplar at Woodville was high pruned maybe to the disadvantage of the trees at lower densities. In contrast, the minor differences between Ruakura and Poukawa in the relationship between DBH of alder and tree density were because of genetic and other factors since the trees were established using nursery-raised plants grown from open-pollinated seed rather than clonal material.

The significantly greater mean root mass density in TP than adjacent Open systems highlighted the benefit of spaced trees of poplar and alder for increasing below-ground biomass and potential contributions to organic matter status and carbon storage, and to aggregate and pore structure and function. Soil organic matter and physical structure are the two soil attributes that underpin all soil processes and services (Dominati *et al.* 2010). Pasture and tree roots were not distinguished in the TP system at each site so it was not possible to determine the relative contribution of each component to root mass density. It is likely that competition occurred between the roots of trees and pastures (Eastham and Rose 1990; Dawson *et al.* 2001; Cubera *et al.* 2012; Rolo and Moreno 2012), resulting in differences in the distribution of pasture root mass density in the two systems. The dramatic decline in root mass density with depth is typical of the decline in various root attributes with depth in a range of ecosystems in New Zealand and overseas (Tufekcioglu *et al.* 1999; Schenk and Jackson 2002; Schenk 2008; Douglas *et al.* 2010; Dodd *et al.* 2011). The exception to this trend found at Ruakura, where root mass density of the alder-pasture system was similar at all depths to 1000 mm, was because of the occasional presence of alder roots >5 mm diameter at depths of 400-600 mm and 600-1000 mm. There was nothing anomalous about the trends for adjacent pasture at the site where root mass density decreased with increasing depth.

The analysis of data for tree centres showed that at Poukawa, root mass density at any tree density significantly exceeded that in open pasture. This has implications for the economics of planting the species, enabling low densities to be established to achieve higher levels of root concentration in soils compared with pasture, without the resulting reductions in understorey pasture production that likely occur at higher tree densities or with canopy closure, as with other species (Douglas *et al.* 2006a; Guevara-Escobar *et al.* 2007). The findings at Ruakura supported the use of alder to increase root mass density in pastoral soils at 600-1000 mm depth. Poplar root mass density at Centre locations at Tikokino and Woodville was unaffected by tree density and the different responses between poplar and alder may be because of inherent variation between the species in tree root distribution patterns or interaction with site-specific factors. The up to 3-fold greater root mass density at 1 m than at Centre locations at each site was due to the sampling regimen, and reflected a decrease in root presence with distance from a tree. However several interactions between main effects (density, depth, location) for root mass density indicated that responses were complex and were site-specific.

Root tissue turnover probably contributed to variation in total carbon mass found in this study, but root mass as a contributor to the potential root turnover pool appeared to have negligible association with total carbon mass to 1 m depth (Figure 24), and interpretations were similar using data for either tree position (Centre, 1m) (not presented). Studies are required in TP systems to determine the relative contribution of root tissue turnover, litter inputs and root exudation to carbon mass in soil profiles in geo-climatically different sites.

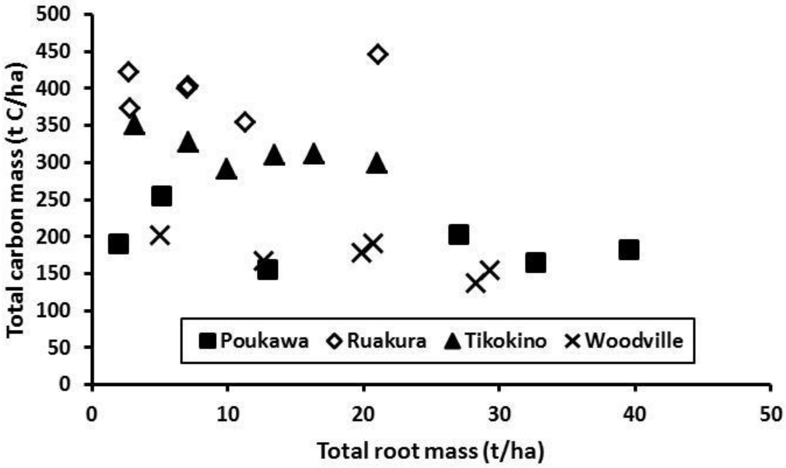


Figure 24. Total carbon mass (t/ha) vs. total root mass (t/ha) (0-1 m depth) at four sites for Open and five tree densities, averaged over positions (Centre, 1 m) and replicates (*n*=3 (Open) or 2 (tree)).

Across the four sites, mean C concentration was within range of those estimated for various pastoral soils such as 5.0-5.6% (0-50 mm depth) (Ross *et al.* 2013), 2.7-4.2% (0-75 mm) (Schipper *et al.* 2013), and 7.7% (0-100 mm) (Mudge *et al.* 2011). A feature of the soil C concentration results was the 2-3-fold greater concentration at Tikokino and Ruakura than at Poukawa and Woodville. An important distinction between Tikokino and Ruakura and the other two field locations is soil type. The volcanic soils at Tikokino and Ruakura are known to accumulate more organic C than the sedimentary soils found at Poukawa and Woodville. Soils beneath trees at Tikokino and Ruakura also had lower mean bulk density (0.69 and 0.78 g/cm^3, respectively) than those at Poukawa and Woodville (1.00 and 1.19 g/cm^3, respectively), potentially enhancing root proliferation and tissue turnover, and contributing to C stocks, although the total standing root mass showed a greater range in the sedimentary soils (Figure 24). The soil difference over-rode the differences in C inputs and outputs over time (Amundson 2001) from the well-developed tree canopies at each site, enabling potentially significant litter inputs, differences between alder and poplar litter in their rate of decomposition and concentrations of resulting nutrients (Pérez-Corona *et al.* 2006), and the fact that alders were planted at both Ruakura and Poukawa, while poplars were growing at Tikokino and Woodville. It also over-rode the differences in pasture production because Ruakura and Woodville grew 16 t DM/ha/yr compared with 10 t DM/ha/yr at Poukawa and Tikokino.

Soil C concentration in the TP systems, whether involving all tree data or only those for Centre locations between trees, did not increase compared with the Open systems as found or implied in other studies (Gupta *et al.* 2009; Ramachandran Nair *et al.* 2009; Haile *et al.* 2010). However there were exceptions. At Poukawa, C concentration in soil in the Centre locations at Medium-high tree density exceeded the Open system by 26%. The reverse was also found. At Ruakura, the Open system had greater C concentration in soil than adjacent TP systems in the top 150 mm of the soil profile, whereas at 150-1000 mm depth, no differences in C concentration in soils were found between the two systems. This result could not be explained by trends for root mass density because this attribute was approximately constant at all soil depths in the TP system whereas in Open, it declined significantly with depth. Separate samples were collected for soil C and root mass and it is therefore possible that spatial variability accounted for some of the observed results. Determining the proportion of live, fine roots in the different depth increments in future studies would aid interpretation. The prominent decrease in soil C concentration with increasing depth at all sites aligns with a commonly observed trend in temperate pastoral ecosystems (Groenendijk *et al.* 2002;

Condron *et al.* 2012), although this study also showed that responses were sometimes different in the Open and TP systems, depending on site.

The variable responses of soil C concentration to tree density at each site precluded making general planting recommendations. At Poukawa, higher tree densities resulted in elevated C concentrations of soil whereas at Tikokino, the reverse trend occurred with higher concentrations detected at lower tree densities. There was no effect of tree density on C concentration at Ruakura or Woodville. Tree density is known to affect a number of below-ground attributes (Puri *et al.* 1994; Perrott *et al.* 1999; Power *et al.* 2003; Douglas *et al.* 2010; Nyakatawa *et al.* 2011), but this is believed to be the first report of its effect on soil C concentration to 1 m depth. The higher C concentration at 1 m than Centre locations at Poukawa and Woodville, and a similar trend at Ruakura and Tikokino, may be because of the potentially higher C inputs available from the higher root mass density found at 1 m locations at all sites.

Soil C mass (0-75 mm depth) beneath poplar stands at Woodville (40 t C/ha) was 26% greater than found by Guevara-Escobar *et al.* (2002) beneath mature poplars at 37-40 sph in Pohangina, Manawatu (31.7 t C/ha), whereas the value at Tikokino (56 t C/ha) was about 75% greater than calculated by Guevara-Escobar *et al.* (2002). The Woodville and Pohangina sites have similar climate and soils, which may partly explain their relatively close C estimates compared with those for Pohangina and Tikokino. Carbon mass beneath trees has often been measured in surficial soil layers (Ross *et al.* 1999; Guo and Gifford 2002; Laganiere *et al.* 2010) but this study provided compelling evidence for measuring C mass in deeper soil layers by showing that it was a significant proportion of total C mass to 1 m depth. For example, at Poukawa and Tikokino, C mass within 300-1000 mm depth was about 50% of total C within the 1 m profile. It is possible that measurement deeper than 1 m would identify additional significant C stocks. In this study, estimates of total C to 1 m depth ranged from 165 t C/ha at Woodville to 410 t C/ha at Ruakura, which highlighted the spatial variability that exists in this attribute, and hence the need to be cautious in extrapolating findings to other sites.

Using individual bulk density values to calculate C mass is practised routinely (Goidts *et al.* 2009; Marchão *et al.* 2009; Dodd and Mackay 2011; Throop *et al.* 2012) and this study confirmed the value of this approach because of its impact on results and their interpretation. Measurement of horizon lengths within the 1 m profiles may have assisted further with interpretation of results. Carbon mass at Ruakura and Tikokino exceeded by approximately 2-fold the C mass at Poukawa and Woodville, despite marked differences in primary production levels and in the tree species present.

At Tikokino, the total C mass in the soil of the Open system was 31% greater than in the TP system, as it was at Woodville with the Open being 23% greater than in the TP system. In fact C mass at Tikokino at all tree densities was 19-30% less than in Open. Differences in C mass between densities at Woodville, with the exception of the medium density, were 11-49% greater in the Open system. At Ruakura and Poukawa there was no difference in C mass between the Open and TP system (Table 12), but there was a trend of higher C mass in the TP than Open systems at both sites. It is interesting to speculate on the apparent C mass differences between the Open and TP systems at Tikokino and Woodville compared with Ruakura and Poukawa. The common thread would appear to be the tree species, with poplar at Tikokino and Woodville, and N-fixing alder at Ruakura and Poukawa. The study suggests that tree species over-rode differences in primary production levels (Ruakura and Woodville > Tikokino and Poukawa), soil type (Ruakura and Tikokino with volcanic soils vs. Poukawa and Woodville with sedimentary soils), soil C concentrations (Tikokino and Ruakura > Poukawa and Woodville), root production (TP > Open system at all sites), bulk density

(Poukawa and Woodville > Tikokino and Ruakura) and C mass (Tikokino and Ruakura > Poukawa and Woodville) between distinct field sites, with poplar planting reducing soil C at Tikokino and Woodville, while the alders at Ruakura and Poukawa had a neutral or positive impact on soil C mass.

The results for total C mass to 1 m depth which indicate that TP systems had less C than Open systems at Tikokino (24% less) and Woodville (19%), despite distinct geo-climatic and soil type differences between these two sites, challenges the meta-analysis of Guo and Gifford (2002) that reported planting of broadleaf trees (e.g. *Eucalyptus* and *Populus*) into pasture had little effect on soil C stock. This conclusion would appear to require updating given the findings of the present study, which suggests that tree species may be an additional factor influencing soil C accumulation. Results may be because of variation in the level of N inputs by the N-fixing alders (Sharma *et al.* 2009; Uri *et al.* 2011; Perakis *et al.* 2012) at the different densities and consequent effects on plant growth responses and decomposition products for incorporation into the soil C pool. Alders also have the potential to raise soil C levels in these soils where N rather than C often limits organic C accumulation. Poplars on the other hand are known to increase soil pH (Guevara-Escobar et al., 2002). Poplar roots and their exudates may be mobilising deep soil C otherwise stable in an Open system. This is distinct from the influence *Pinus radiata* is known to have on soil pH and soil C when planted into pasture land (Parfitt and Ross 2011), although not always (Alfredsson *et al.* 1998).

Ordinal categories were used to describe tree density in the main study which simplified analyses and aided comparisons. Actual densities were very similar for Poukawa, Tikokino and Woodville so that results would have been unchanged compared with the approach taken. Despite the relatively wide range in tree density at Ruakura (112-1276 sph), no significant effect of density on attributes was found. This suggests that if the density range was similar to that at the other sites, the same interpretations and conclusions would have been reached. This is of considerable significance because the tree density used in soil conservation plantings varies with rock and soil type, erosion type, tree species and climate and so can be found at densities as low as 20 and as high as 200 trees per hectare (Wilkinson 1999; Cairns *et al.* 2001).

Another consideration is that each site was located on flat or slightly sloping land, which is atypical because the vast majority of wide-spaced trees in New Zealand are used on erodible hill country (Van Kraayenoord and Hathaway 1986a; Van Kraayenoord and Hathaway 1986b; Wilkinson 1999; Cairns *et al.* 2001). Spaced trees have quite different above- and below-ground development with increasing slope angle (Chiatante *et al.* 2002; McIvor *et al.* 2009), although this depends on factors such as species, soil texture, and age (Stokes *et al.* 2009). Different growth forms could have significant effects on nutrient cycling and soil C inputs.

5.4 IMPACTS OF SILVOPASTORAL SYSTEMS ON GREENHOUSE GAS EMISSIONS

The complex interactions between livestock, trees and pasture, as they influence the living environment and associated GHG emissions from sheep and beef in open pasture and tree-pasture farming systems, captured in the modelling, was limited to the influence of the tree on pasture production (and corresponding carrying capacity), reproductive performance (i.e. lambing and weaning %), and as a source of supplementary feed. Other potential benefits (i.e. reduced soil losses, soil stabilisation, increased soil carbon capture, increased soil pH, improved animal performance via reduced heat stress and savings in grazing energy expenditure) have not been addressed. Therefore, the full potential of having areas at risk from erosion under wide-spaced-planted trees remains to be fully explored.

The short-term nature of the modelling exercise implies that caution is required when extrapolating these results to longer periods of time. Because of the scaling step to achieve maximum pasture utilisation to make all farms comparable, annual pasture utilisation was optimised. These values represent higher pasture utilisation than reported as ‘average’, and hence, greater carrying capacities were achieved relative to the average WLNI Farm Monitoring 2012 system. Notwithstanding these limitations, the current modelling exercise demonstrated farming opportunities for reducing total GHG emissions and emissions intensity from sheep and beef under mixed, tree-pasture farming systems.

Because of the intrinsic link between DMI and methane emissions (that accounted for up to 70% of total GHG emissions), efficiencies in terms of feed conversion are critical to the achievement of emission-efficient farms. Feed conversions achieved by the Tree plus intake scenarios (Trees_I100 and Tree_I25; 22.6 kg DMI/kg meat and fibre) were more efficient than that of the Open scenario (24.2 kg DMI/kg meat and fibre).

Increased weaning % represents a greater amount of lambs, and corresponding meat product, produced per breeding ewe. These measures were captured in overall greater ewe efficiencies (64.5 vs. 54.7 kg of weaned lamb weight per kg ewe mated), reflecting a greater feed energy shift of the Tree_ scenarios towards production rather than maintenance (Table 17). Further, the Open scenario showed a slightly greater proportion of maintenance DMI (the sum of breeding ewes, ewe replacements and rams DMI) relative to total DMI, compared with the Trees_ scenarios; 0.59 vs. 0.57.

Reproductive rates used in the current modelling exercise were in agreement with those reported by McWilliam *et al.* (2004) for ewes fed different levels of poplar supplementation; ewe lambing % for the Tree_I_ scenarios was set at 154%, similar to the 155% reported by McWilliam *et al.* (2004) for the highest level of poplar supplementation tested (1.5 kg of fresh poplar cuttings offered daily during mating).

Replacement rates, however, remained unaltered among scenarios; reducing the breeding ewe replacement rate has proven to be an effective managerial GHG mitigation option across a broad range of sheep and beef farming systems in New Zealand (Duchemin 2011). A kinder environment under tree-pasture systems provides for more predictable outcomes (i.e. weaned lambs) and is less likely to have large losses of lambs in a storm event. Expectedly, anecdotal evidence suggests that breeding ewes in such environments would be kept for longer, and fewer replacements would be needed to maintain the same breeding ewe numbers.

Management options that reduce the proportion of feed energy expended on animal maintenance and increase the proportion of energy expended on production are often effective in reducing emissions intensity (kg CO_2-e/kg of meat and fibre) (Table 5). The breeding phase often contributes the largest proportion of total GHG emissions from livestock production systems (Grainger and Beauchemin 2011). As a consequence, the Open scenario was associated with greater total emissions (4832 vs. 4265 kg CO_2-e/ha for the Open vs. Tree_0 scenarios, respectively) and with greater emissions intensity (15.9 vs. 14.5 kg CO_2-e/kg of meat and fibre for the Open vs. Tree_I100 scenarios, respectively).

Often, farmers are faced with the possibility of reducing both total emissions and emissions intensity on sheep and beef farms via changes in farm management, without a major impact on profitability. Emissions intensity can potentially be reduced more readily than total emissions. The magnitude of the reductions may seem small on an individual basis, but when adopted on a larger scale, it could provide for a significant contribution to New Zealand’s total emissions liability given the high proportion of GHG emissions originating from agriculture.

6. Conclusions

Tree-pasture systems involving poplar and alder aged 14-16 years at a range of densities had mean total soil C masses (0-1000 mm depth) of 165-410 t C/ha across four geo-climatically different sites in the North Island. At each site, total soil C mass was similar in TP and adjacent Open pasture systems. The effect of tree density was equivocal with an increase or decrease in soil C with increasing density, or no distinct pattern.

Total soil C mass was lower in the poplar-pasture than adjacent Open pasture systems at Tikokino and Woodville, despite marked differences in geo-climatic characteristics (Table 19). At Ruakura and Poukawa, again with contrasting geo-climatic attributes, total soil C mass was similar in the alder-pasture and adjacent Open pasture systems. There was a suggestion it was in fact higher at Ruakura under the alders. The findings of this study suggest that tree species may be an additional factor influencing the C cycle and C accumulation in soils and this needs to be added to the factors considered in the building of our soil C inventories, in addition to the C stored in the above- and below-ground biomass of the trees. Estimates of the amount of C stored in the tree will be determined by tree age, and also by the tree density, which will vary widely depending on the erosion type requiring stabilisation.

Table 19. Summary of the influence of the four tree-pasture systems on total soil C mass and greenhouse gas emissions.

	Total Soil C mass to 1000 mm (t C/ha)				**Greenhouse Gas emissions** (kg $C0_2$-e/ha/year)	
	Open Pasture		**Tree-pasture**		**Open pasture**	**Tree-pasture**
Soil Order	Pasture Production (t DM/ha/yr)		Pasture Production (t DM/ha/yr)			
	16	10	16	10	4832	4265[1]
Volcanic Bulk density <0.8 Anion storage High	Ruakura 348	Tikokino 396	Ruakura 410 (+18%)	Tikokino 302 (-24%)	**Carbon in standing tree shoot and root biomass[2]**	
Sedimentary Bulk density >1.0 Anion storage Low	Woodville 203	Poukawa 187	Woodville 165 (-19%)	Poukawa 192 (+3%)	Influenced by DBH and planting density	

[1] Through a combination of greater feed conversion efficiency, lower maintenance and higher reproductive performance

[2] At 50 stems per hectare, 12 year old poplar on a slope of 15° with a DBH 31 cm, height 16 m and canopy width of 7 m, estimated to have above-and below ground biomass of 250 and 63 kg, respectively, with most (79%) of the below-ground biomass within 2 m radius of tree and about 1 m depth (Douglas et al., unpubl.), would contain 6.3 tonnes of carbon per hectare, assuming the carbon content of the biomass was 40%.

A modelled hill country sheep and beef farm with various silvopastoral systems found slight advantages from TP compared with Open pasture systems (Table 19). These included increased animal reproductive performance, higher feed conversion efficiency, reduced total GHG emissions (4265 vs. 4832 kg CO_2-e/ha) and reduced emissions intensity (14.5 vs. 15.9 kg CO_2-e/kg of meat and fibre). The annual reduction of 567 CO_2-e/ha/ yr is significant when aligned with the changes in carbon in the soil and stored in the tree biomass over time. As the quest for further productivity gains in the sheep and beef sector through on-going advances in fecundity, lamb survival to weaning, live weight gain and longevity continues, these advantages are likely to become larger with a tree-pasture system better able to provide the living environment required for these to be captured by the farmer.

7. Recommendations

1. Soil C mass should be determined to at least 1 m depth because C deeper in soil profiles is a significant component of the total C stock.
2. Determine if the soil C mass differences found in this study are applicable to tree densities on hillsides where the vast majority of wide-spaced tree plantings are found.
3. Initiate a more detailed study to explore the factors contributing to the loss of soil C from the poplar tree-pasture system compared with the alder tree-pasture system. This should include sites with variable geo-climatic and soil type differences.
4. The findings of this study should be aligned with studies to date on *Pinus radiata* and recent study of the influence of perennial horticultural plants including apples and kiwifruit, as part of a wider investigation of the influence of trees, as distinct from pasture species, on soil carbon.
5. A number of potential benefits of silvopastoral systems were excluded from the current modelling exercise. Inclusion of these, and the carbon stocks in the tree biomass as part of the carbon budget in future scenario tests, would strengthen knowledge on the impacts of tree-pasture compared with open pasture systems.

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