

Will wide-spaced silvo-pastoral plantings maintain soil carbon stocks?

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Abstract

Silvo-pastoral systems are common globally but not so in New Zealand, where there are limited examples within pastoral landscapes. Pastoral soils in New Zealand have relatively high soil organic carbon (SOC) stocks by global standards, and tree planting may reduce these. This study aimed to investigate whether wide-spaced tree planting into pasture would maintain SOC stocks after 25-27 years, extending the data previously reported at 14-16 years after planting on two North Island pasture sites. Two deciduous tree species were planted in the late 1990s in part-Nelder experimental designs – poplars (*Populus deltoides* × *P. nigra*) at a summer-moist site, and alders (*Alnus cordata*) at a summer-dry site. Soil OC stocks to 600 mm depth were re-measured in 2023, under open pasture and two tree stem densities at each site, along with pasture herbage accumulation and micro-climate variables. Soil OC stocks had continued to decline under the poplars but were relatively stable under the alders. Pasture production was c. 60% of open pasture under the poplars but not reduced under wide-spaced alders (120 stems/ha). The nitrogen-fixing capability of the alders may be an important function in this silvo-pastoral context, offering nitrogen input for additional biomass C sequestration without compromising pasture productivity and SOC stocks.

Keywords: Alder, herbage accumulation, Part-Nelder design, poplar, soil organic carbon

Introduction

Silvo-pastoral systems are used in many livestock production contexts globally (Jose & Dollinger 2019), but rarely in New Zealand. In New Zealand, the main application is wide-spaced trees used for erosion control. Pasture and radiata pine combinations were well studied prior to 2000 (Knowles 1991; Chang et al. 2002). A substantial amount of research with other tree species was conducted in New Zealand during the 1990-2010 period, largely out of AgResearch and Massey University (Guevara-Escobar et al. 1999; Power et al. 1999; Devkota et al. 2000; Douglas et

al. 2006). This work tended to focus on the impact of wide-spaced trees on understory pasture production and soil nutrient and moisture status (Benavides et al. 2009), with the general view that trees would reduce pastoral productivity and the benefits (erosion control, alternative product, animal welfare) would be insufficient to offset those losses (Parminter et al. 2001). A more recent modelling analysis incorporates additional factors and presents a more favourable view (Vibart et al. 2015).

With the advent of carbon (C) as a viable economic product from farm systems (Funk et al. 2014), silvo-pastoralism offers new potential revenue streams in terms of vegetation stock accumulation within an Emissions Trading Scheme policy framework. The other major potential C stock within farm systems is associated with soil organic matter. Of all land uses, perennial grasslands tend to maintain the highest soil organic carbon (SOC) stocks globally (Conant et al. 2011) and our high productivity pastures in New Zealand with high nitrogen (N) inputs typically have relatively high soil carbon stocks (Schipper et al. 2017). This has led to a view that there is limited potential for further increases in SOC stocks to offset emissions within farm systems (Eckard & Clark 2018), although some management options have been explored (Whitehead et al. 2018). Full afforestation of grassland, this is the establishment of a forest or stand of trees in an area where there was no recent tree cover, is generally shown to reduce SOC (Davis & Condon 2002; Bárcena et al. 2014). Partial afforestation, as implemented in silvo-pastoral systems, may not lead to such SOC losses, reducing the risk that above ground vegetation carbon stock gains from afforestation will be tempered by SOC stock losses.

One of the major challenges with measuring SOC stocks is its spatial and temporal variability, particularly in the highly variable topography of many New Zealand pastoral systems. Soil carbon is a large pool that varies across and within paddocks (McNally et al. 2024) and changes slowly (Schipper et al. 2017). Because of these limitations, large sample numbers are required to detect significant changes as a result of

management (Glover-Clark et al. 2024). Therefore, the ideal measurement scenario for assessing the impact of a long-term management change (such as silvo-pastoral planting) on SOC is sufficient sample duplication over periods of >5 years.

The objective of this study was to re-visit two silvo-pastoral sites, established in the late 1990s and measured for soil carbon stocks in 2012, 14-16 years after tree planting (Douglas et al. 2020). A re-measurement aimed to determine whether the minimal changes identified at that time had resolved into significant differences between open pasture and spaced tree planted sites, now 25-27 years after planting, within a single paddock planted at varying tree stem densities.

Materials and Methods

Site Selection

This study was conducted on two farms that both have part-Nelder tree plantations that were established in the late 1990s (Woodville in 1996, and Poukawa in 1998). Site details are given in two papers that describe the results of a similar sampling in 2012 (Douglas et al. 2016; Douglas et al. 2020). In summary, Woodville is a summer-moist site located on Ballantrae Hill Country Research Station in the southern Hawke's Bay (40°18'57" S 175°50'23" E, 129 masl). The soil type is Raumatī silt loam (Gley) with a slope of 5-15°, planted with poplar (*Populus deltoides* × *P. nigra*). Poukawa is a summer-dry site located on the former Poukawa Research Farm in central Hawkes Bay (39°45'18" S 176°43'29" E, 53 masl). The soil type is Matapiro silt loam (Pallic) with a slope <5°. Poukawa has been planted with Italian alder (*Alnus cordata*). The designs involve a radial planting of increasing tree spacing, enabling a space-efficient assessment of the effect of planting density on understory vegetation and soils (Nelder 1962). Both sites are regularly grazed by sheep. Historic nutrient management included phosphorus (25 kg P ha⁻¹) and sulphur (20 kg S ha⁻¹) applications, with little or no use of N fertilisers. At each site, two tree stem density locations were selected within the design having understory pasture. At Woodville these consisted of low and medium tree stem density (c. 65 and 250 stems/ha, respectively). At Poukawa these consisted of low-medium and medium-high tree stem density (c. 120 and 550 stems/ha, respectively), both compared with open pasture sites occurring in unshaded areas at least 10 m away from tree canopies within the same paddock. Three replicate plots in the area between four trees within each tree stem density, and four replicate plots in the open pasture area, were established for climate, pasture and soil measurements.

Environmental

Climate variables at both sites were measured

over a full year, from January-December 2024. Air temperature was measured daily using a Watchdog 2000 weather station. Manual rain gauges at 1.2 m height were used to measure monthly rainfall over open pasture at both sites with additional gauges under the low and medium tree density canopies at Woodville to measure throughfall. Volumetric soil moisture content was measured under the low and medium stem density, and open plots at Woodville using a 12 cm time-domain reflectometry probe (Field Scout TDR 350) every month. Soil temperature was measured at three-hour intervals under the three treatments at Woodville using Thermocron iButtons (model DS1921G). These were placed at 10 cm depth in the soil and recovered and replaced monthly.

Vegetation

Pasture production was measured using a double-trim exclusion cage method (Radcliffe 1974) between 1 December 2023 and 30 November 2024 at both sites. Three 0.5m² cages were placed on top of pre-trimmed pasture within each replicate of the tree density treatments. The herbage was cut approx. monthly over one year to 3 cm height, weighed moist, oven dried for 48 h at 65°C and weighed to obtain kg DM/ha equivalent herbage accumulation. To account for leaf litter from trees, a trap was placed within each replicate plot under the tree canopy (0.32 m² at Woodville and 0.21 m² at Poukawa). The traps were emptied monthly, the litter weighed moist, and oven dried for 48 h at 65°C to determine kg DM/ha equivalent contribution.

Tree canopy cover was measured monthly using a cell phone app (Canopy Cover by Hsien Ming Eason). Measurements were taken at five positions within the plots and an average recorded given as a percentage of canopy cover.

Soil sample collection and analysis

Soil carbon concentrations and soil bulk density in five layers past a depth of 600 mm had been measured on these sites in October 2012 as described in Douglas et al. (2020). The data from the equivalent tree stem density arcs of the part-Nelder at each site were included in the present study to analyse change over time.

In November 2023, both sites were re-sampled, with samples collected from three replicates of the low and medium (Woodville), and low-medium and medium-high (Poukawa) stem density, and open pasture treatments. A diagram of the sampling design is shown in Figure 1. Following the same protocol as Douglas et al. (2020), the soils were sampled past a depth of 600 mm at increments of 0-75, 75-150, 150-300, 300-600 and >600 mm using a 50 mm diameter hydraulic corer on the back of a modified light utility vehicle. Five duplicate cores were taken from each sampling position and bulked by depth increment. These cores had rocks

and roots >2 mm diameter removed by sieving before being oven-dried at 40°C for 48 hours and ground in a mill. Samples were analysed in an Elementar varioMAX cube for total C concentration (%).

The SOC stock (Mg C/ha) of the fine earth fraction for each depth sample (i) was calculated using Eq. 1 below.

$$\text{SOC stock}_i \left(\frac{\text{Mg C}}{\text{ha}} \right) = \frac{[\text{SOC}]_i}{100} \times \text{Bulk density}_i \left(\frac{\text{Mg}}{\text{m}^2} \right) \times \frac{\text{layer depth}_i \text{ (mm)}}{1000} \times 10000 \left(\frac{\text{m}^2}{\text{ha}} \right)$$

The profile SOC stock over all layers for each sample site was calculated on an equivalent mass basis (Wendt & Hauser 2013) by adopting the 2012 mean soil masses to 600 mm for each site-stem density combination as standards. This mass was approx. 800 Mg/m². The equivalent mass SOC stock for each 2023 measurement was then calculated using the relevant mean soil mass from the 2023 bulk density profile measures and a cubic spline interpolation of the known points of the soil mass versus SOC function with depth.

Statistical analysis

Pasture harvested was accumulated by season (Summer = December-February; Autumn = March-May, Winter = June-August, Spring = September-November), assuming constant daily growth rates where harvest periods crossed seasonal boundaries. The results for each site were analysed separately using generalised linear models with gamma-distributed errors and log link functions. Fixed effects of season (four levels) and stem density (three levels) as well as interactions were included. For the Poukawa site non-constant

variance necessitated estimating dispersion separately for each stem density level, and site seasonal herbage accumulation values of zero were increased to 1 kg DM/ha. Confidence intervals (95%) for estimated mean herbage accumulation values were back-transformed from the log scale and are hence not symmetric.

At the Woodville site, two SOC percentages from the 2012 data, recorded in the 300-600 mm layer, were considered unrealistically high (>2%) and replaced by the mean values of the remaining replicate plots. Similarly, two bulk density values from the 2023 data, recorded in the 300-600 mm layer, were considered unrealistically low (<0.95 g/m³) and replaced by the mean values of the remaining replicate plots. For each site, equivalent mass 600 mm carbon stock values were fitted using multivariate gaussian regression models with fixed effects of stem density (3 levels) and year (2 levels), including interactions. Due to non-constant variance, dispersion was estimated separately for each stem density level at Woodville, and each year level at Poukawa.

All multivariate regression models were fitted in the R statistical computing environment (R_Core_Team 2024) using the glmmTMB package (Brooks et al. 2017).

Results

Site climate characteristics

Cumulative rainfall from January 2024 to December 2024 was 1397 mm at Woodville and 695 mm at Poukawa, with a pronounced wet summer at Woodville

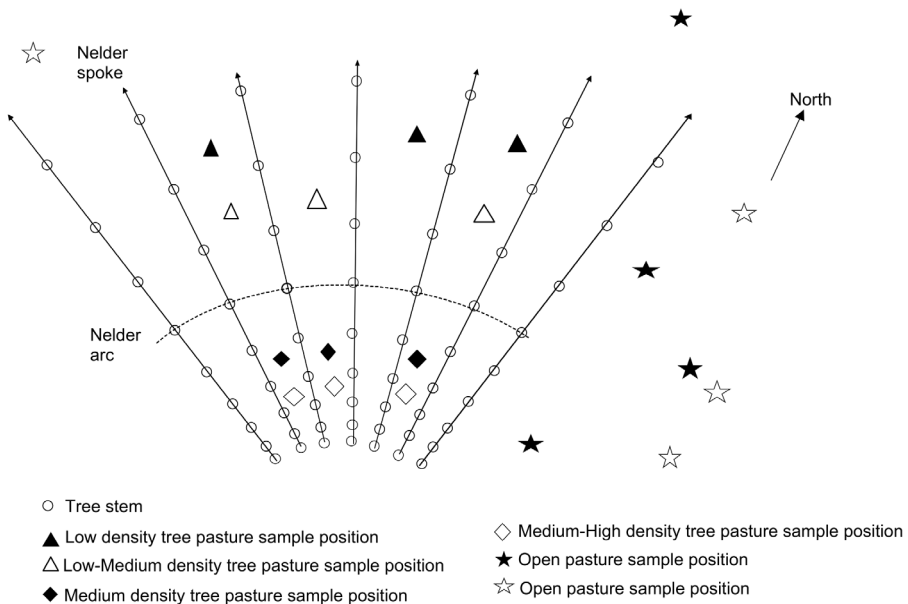


Figure 1 Sampling positions within the part-Nelder design at both sites. Closed symbols represent Woodville sites and open symbols represent Poukawa sites (Adapted from Douglas et al. 2020).

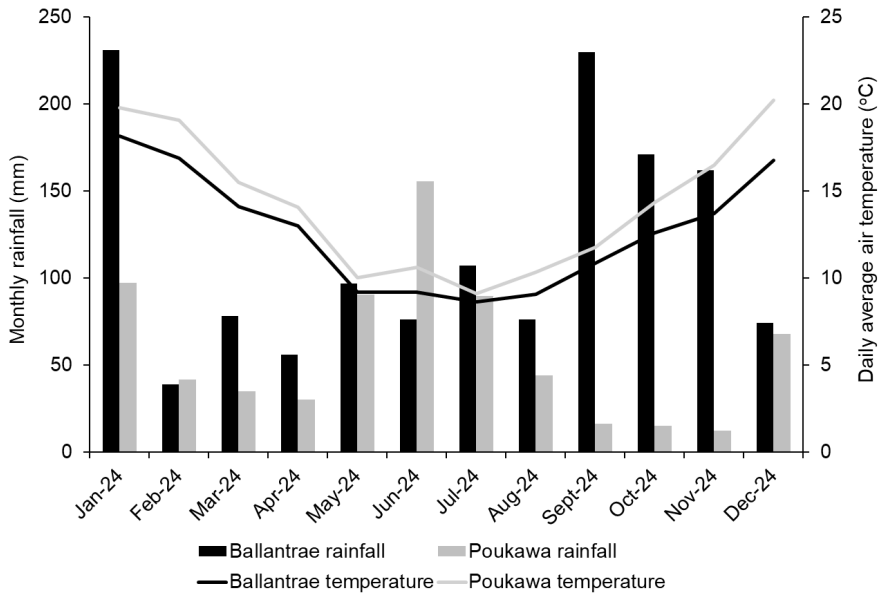


Figure 2 January-December 2024 climate data for the two part-Nelder sites.

and a pronounced dry spring at Poukawa (Figure 2). Throughfall under the poplars at Woodville was reduced to 1180 mm at the low tree density and 1104 mm at the medium tree density, respectively. These reductions varied from 0-29%, on a monthly basis, for the low and low-medium tree density and between 5-52%, on a monthly basis, for the medium and medium-high tree density, respectively.

At Woodville, mean annual soil temperature was 13.6°C under the open pasture, and was on average 1.2°C and 2.3°C cooler under the low and medium tree density, respectively. These reductions in temperature under the tree canopy ranged from 0.3 – 2.6°C (low) and 0.7 – 3.2°C (medium) in the summer and winter periods.

Volumetric soil moisture in the pasture rootzone at the Woodville site ranged between 22% (January) to 54% (September), and it was on average 3.0% and 3.4% units greater under the low and medium tree density canopies, respectively. Calibration of the TDR probe data measured with 12 cm pins against physical soil moisture measurements, indicated that these values were effectively similar to gravimetric soil moisture contents within the 0 – 75 mm soil depth layer.

Pasture herbage accumulation

At Woodville, the pasture production between 1 December 2023 and 30 November 2024 was 8360 kg DM/ha in the open pasture plots. This was reduced by 60% and 58% at the low and medium density plots, respectively, relatively consistently across all seasons (Figure 3a). At Poukawa, the total annual pasture production during the same period was 5480 kg DM/

ha in the open pasture. This was reduced by 90% in the medium-high plots, where no growth occurred in summer and autumn. The low-medium density plots had 16% greater annual pasture production compared to open pasture ($p < 0.05$), with this difference mainly expressed in autumn (Figure 3b).

Tree measurements

Canopy cover of the poplars at Woodville ranged from 12% in mid-winter to 54% in mid-spring in the low density plots, and from 22% to 75% in the medium density plots, respectively. For the alders at Poukawa, peak canopy in mid-spring was 22% in the low-medium density plots and 51% in the medium-high density plots, respectively.

Leaf litter fall between March – June from the poplars at Woodville was 2200 kg DM/ha equivalent under the low tree stem density plots and 2990 kg DM/ha equivalent under the medium tree stem density plots, i.e., 36% greater under the medium density. At Poukawa, leaf litter fall between April – July from the alders was 2120 kg DM/ha equivalent under low-medium tree stem density, and 7740 kg DM/ha equivalent under medium-high tree stem density, i.e., more than 2.5 times greater under the higher density.

Soil organic carbon

The measurement year effects on soil carbon stocks (Mg C/ha to c. 0-600 mm) for each tree stem density treatment and each site were very different. At Woodville, there was a significant reduction in SOC stocks between 2012 and 2023 under both the low and medium tree stem densities ($p < 0.01$) but there was

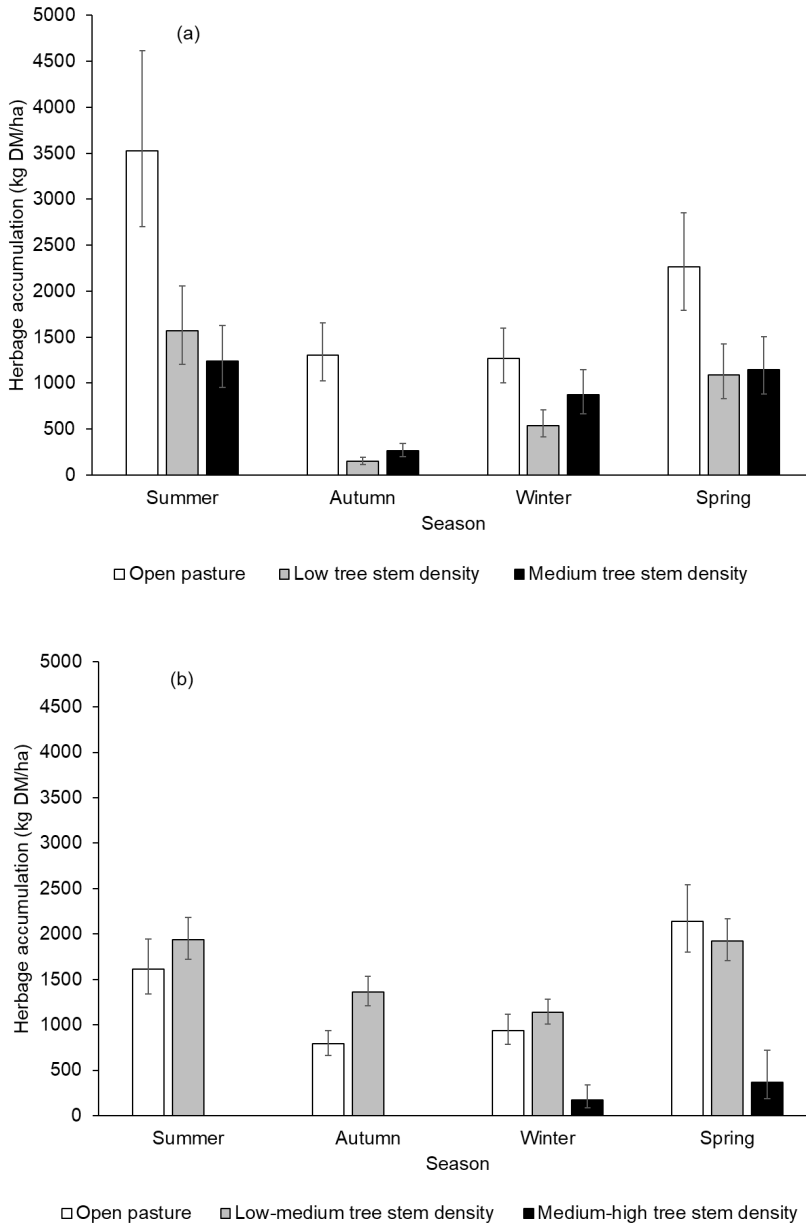


Figure 3 Mean seasonal herbage accumulation in the open pasture and understory plots between 1 December 2023 and 30 November 2024 at the (a) Woodville and (b) Poukawa sites. Error bars represent the back-transformed 95% confidence interval of the mean.

no significant difference between measurement years in the open pasture plots ($p > 0.05$, Figure 4a). The relatively large SE values for the open pasture sites should be noted, 16.1 in 2012 and 11.4 in 2023.

At Poukawa, the opposite pattern was observed. There was a significant reduction in SOC stocks between 2012 and 2023 in the open pasture plots ($p < 0.01$), but there was no significant measurement year effect at the low-medium and medium-high tree

stem densities ($p > 0.05$, Figure 4b). Note however that the p -value for the measurement year effect under the low-medium tree stem density was < 0.10 .

Discussion

The tree stem density areas within the part-Nelders were selected to reflect a silvo-pastoral situation with a reasonable amount of initial pasture cover under the canopy, where sampling had previously been conducted,

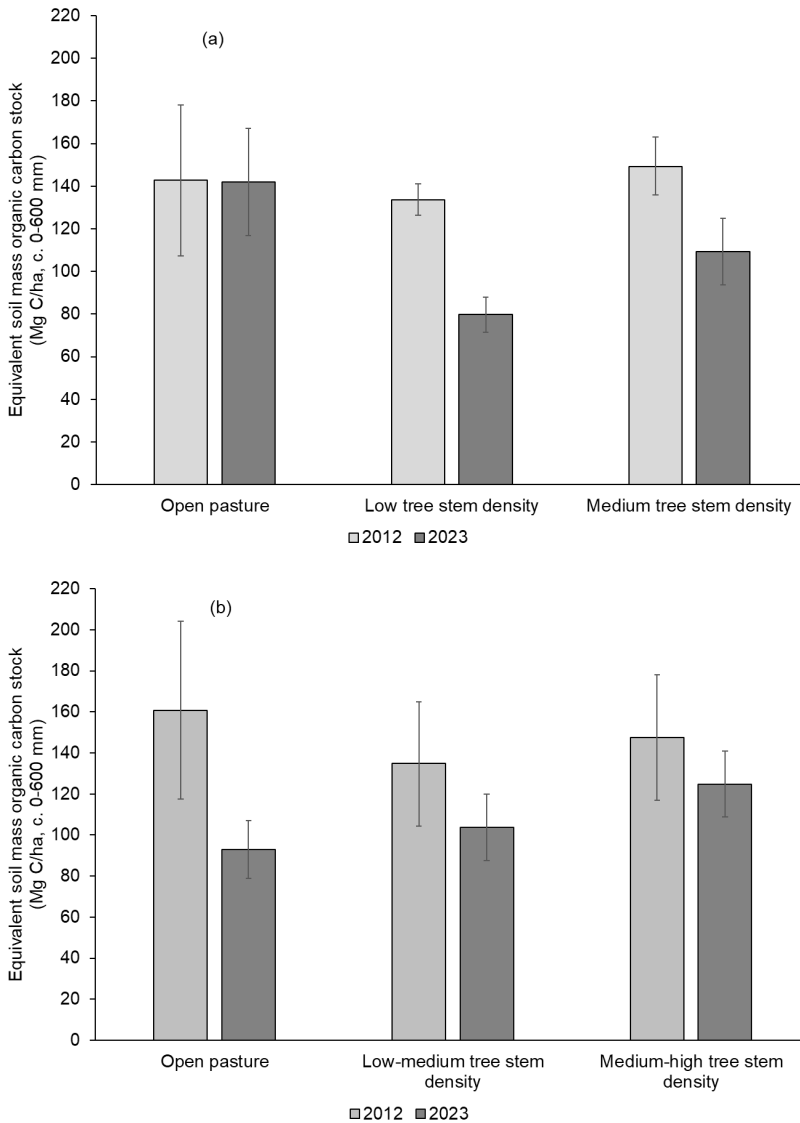


Figure 4 Mean soil organic carbon stocks for an equivalent soil mass (c. 0-600 mm depth, fine earth fraction) under different tree stem densities at a) Woodville and b) Poukawa sites. Error bars represent the 95% confidence interval of the mean.

in order to quantify tree stem density treatment effects over time. Ultimately the medium-high density treatment at Poukawa resulted in little understory pasture regrowth after the plots were initially trimmed, reflecting the very low light transmission environment under 51% tree canopy cover in spring. This canopy level was effectively a complete afforestation situation. Given the marked differences in the tree stem densities, soil types, light environments, and pasture responses, the two sites will be discussed separately.

Woodville poplars

Overall, there was a lower SOC stock under both medium and low tree stem densities compared

with open pasture (Fig. 4a). In 2012, Douglas et al. (2020) observed a marginally significant difference, and suggested these sites had lost SOC based on the assumption that all the open and planted areas had similar initial SOC stocks at planting in 1996 (although this was only observed at planting in terms of consistent topsoil SOC concentrations). The 2023 results were consistent with the pattern observed in 2012 and the decrease under these treatments since 2012 appears to represent an ongoing decline in SOC under the trees over time. The SOC stock rates of change over time under trees were very high (-3.6 to -4.9 Mg C/ha/y) compared to those typically seen in long-term grazed

pastoral systems (0.32 Mg C/ha/y) but these are near the high end of those seen under pasture renewal (4.1 Mg C/ha/y, Schipper et al. 2017).

A reduction in SOC stock indicates an imbalance between gains (via inputs from plant tissue turnover and animal excreta) and losses (via soil respiration and dissolved SOC losses by leaching and runoff). While these processes were not measured in this study, there are some observations we can make based on the climate and plant measurements that were conducted.

Lower pasture herbage accumulation was observed under the tree canopy (Figure 3a), consistent with many other studies (e.g., Power et al. 2001), which would lead to lower shoot and root turnover and lower animal intake and excreta return (Parsons et al. 2009), thereby reducing soil C inputs. However, other research under variable soil fertility and annual herbage yield conditions at Woodville has noted no significant long-term effect on SOC stocks (Mackay et al. 2021), suggesting that C input reductions are mitigated by loss reductions. Under the trees, the observed reduction in soil temperature under the tree canopy may have reduced soil respiration rates and thus soil C losses to air, though the increase in soil moisture may have increased the leaching of dissolved SOC (Ghani et al. 2010). The additional sources of C inputs in tissue turnover from tree leaf litter (estimated at 1–1.4 Mg C/ha/y, assuming 45% C content of leaf tissue), root turnover and root exudation appear to have been insufficient to mitigate the reduction in pasture C inputs (tissue turnover is unknown, but excreta returns can be estimated at c. 1 Mg C/ha/y, assuming 30% of accumulated/consumed herbage is returned). The other contributing C fluxes are difficult to estimate, and a more complete C balance would be a worthy study.

Poukawa alders

There has been little change in SOC stocks at Poukawa under the alders compared with significant losses under open pasture (Figure 4b). The loss of 6 Mg C/ha/y under open pasture is very high in the New Zealand context (Schipper et al. 2017). The 2023 results are also not consistent with the observations in 2012 of no significant difference in SOC from open pasture at either tree stem density (Douglas et al. 2020). It is worth noting that at the low-medium tree stem density (120 stems/ha), understory pasture production was not reduced relative to open pasture (Figure 3b), suggesting that there were tree effects that mitigated the expected loss in pasture production due to shading. Two possible factors may be influential: 1) the summer-dry nature of this site (Figure 2), whereby there is some beneficial effect of the trees on reducing summer-autumn evaporative demand; and 2) additional nitrogen inputs derived from the alders. Power et al. (2001) also observed a lesser reduction in understory pasture production at moderate shade levels

under the N-fixing *Acacia melanoxylon*.

What is somewhat surprising at this site is that the SOC stocks under an effective forest at the medium-high tree stem density (550 stems/ha) were not significantly reduced compared to the other two treatments (Figure 4b). Understory pasture growth was negligible (Figure 3b) and thus pasture tissue C inputs would have been minimal. However, it should be noted that livestock had access to the area and there was evidence of camping behaviour, suggesting ongoing excreta returns. These would have added to the very high leaf litter C inputs – these leaves also have high N content (2.8–3.5%) – which may be facilitating SOC stabilisation.

The Poukawa alder site does offer some potential for a wide-spaced tree system to maintain SOC stocks in addition to the aboveground tree biomass C stocks that have accumulated at this site over c. 27 years since establishment. The lack of a reduction in understory pasture herbage accumulation at the 120 stems/ha tree density suggests no adverse impact on animal production from pasture resulting from tree planting. Indeed there are likely to be notable animal welfare benefits in terms of shade and shelter that contribute to greater overall value from a silvo-pastoral system (Vibart et al. 2015), although implications for greenhouse gas emissions (nitrous oxide, methane) due to grazing should also be included to obtain a complete system C balance.

Wider context

The mean SOC stocks reported for open pastures in 2023 were considerably higher at Woodville (164 Mg C/ha) and lower at Poukawa (99 Mg C/ha) than the mean value of 132 Mg C/ha for flat-rolling dry stock pasture sites on mineral soil across New Zealand, reported by Mudge et al. (2025). On a soil order basis, the Woodville site was much higher than the 1 SE range of Gley soils (115–135 Mg C/ha) and the Poukawa site was lower than the 1 SE range of Pallic soils (110–120 Mg C/ha) reported in Mudge et al. (2025). Our study provides rare data on SOC stocks and changes in silvo-pastoral systems in New Zealand, but robust conclusions are somewhat constrained by the low number of sites and the lack of an overall C balance for the sites. This should include C sequestration in trees, and soil and animal greenhouse gas emissions, components of which have been modelled in Vibart et al. (2015). The estimation of a system full C balance would necessarily be a blending of empirical and modelling data, which could contribute to better quantify the benefits, synergies and challenges posed by the development of silvo-pastoral systems in the New Zealand context.

Conclusions

Under two silvo-pastoral systems that incorporated different sites, soil types and tree species, there was

evidence of both a decline and a maintenance of SOC stocks.

The substantial decline in SOC stocks under the wide-spaced poplar trees at Woodville may be a result of several factors related to lower C inputs and greater losses from soil. Added inputs from tree litter and tree root turnover have not compensated for the likely reduction in pasture tissue inputs from shoot and root turnover at lower pasture productivity levels under tree canopy shading. Initial indications of soil stock losses over the first 16 years since planting have been confirmed over the subsequent 11 years.

In contrast the wide-spaced alders at Poukawa have maintained both pasture production and SOC stocks, offering potential for multiple benefits from this silvopastoral configuration. Given that this was observed on a Pallic soil in a summer-dry environment, the generality of this pattern should be explored elsewhere.

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