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Are native shrubs a sustainable alternative to radiata pine on steep slopes? Insights using bioeconomic model for hill country farms in New Zealand

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ABSTRACT
Limited data on native shrubs has hindered direct comparisons with pine radiata as afforestation options for steep slopes on New Zealand hill country sheep and beef farms. This study updated a native shrub sub-model (NSM) with new research data and developed a radiata pine sub-model (RPM) for integration into a bioeconomic model using STELLA Architect. The model assessed asynchronous afforestation of 10% of effective farm area with either option, comparing impacts on feed supply, sheep dynamics, and farm economics. NSM was updated with growth curve, foliage biomass, and carbon stock data from two New Zealand sites. RPM used literature for growth curve, carbon, and log production data. Simulations included a pasture-only (base) and afforestation with either species at 10% and 20% planting rates. Native shrubs reduced feed supply by 2.5% and 4.0%, while radiata pine reduced it by 7.0% and 7.4% at 10% and 20% planting rates. Reduced feed led to smaller flocks and lower cash flow. Radiata pine generated surplus through carbon and log income, offsetting reduced sheep flock cash flow, while native shrubs did not. Carbon prices of 64.2 and137.4 NZD/NZU would be needed for viability in the best- and worst-case scenarios. Native shrubs are potential land use option on steep slopes but require policy intervention to lower establishment costs and carbon prices.

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Native shrubs; radiata pine; hill country; bioeconomic; carbon stock; sheep; New Zealand

Introduction

Sheep and beef cattle farming is a widespread agricultural enterprise in New Zealand and a major contributor to the economy (Pannell et al. 2021). Approximately, 95% of lamb and 88% of beef produced are exported, accounting for over 16% of New Zealand's total export income (Beef+Lamb NZ 2020a). Over the past 180 years, this farming

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enterprise has expanded to become the dominant land use in the country (Allen et al. 2013), now occupying approximately 63% of New Zealand's agricultural land (Beef +Lamb NZ 2022a). Currently, more than half of the sheep and beef cattle farms are located on hill or hard hill country that is characterised by a mixture of flat, medium and steep slopes (Beef+Lamb NZ 2020c). The expansion of these farms significantly improved both productivity and profitability of the farming sector. However, in some cases, it has also led to negative environmental impacts, particularly due to the clearing of native vegetation for the establishment of temperate perennial pasture (Allen et al. 2013). The environmental impacts of the expansion of sheep and beef farms include increased greenhouse gas emissions, loss of biodiversity, waterway pollution, and soil mass movement (Ministry for the Environment 2022). Soil mass movement is of particular concern in hill country, as it not only damages property but also exacerbates other environmental issues (Basher 2013). This problem is more pronounced on steeper slopes, where instability is often caused by the removal of deep-rooted woody vegetation (Basher 2013). To address these challenges, biological soil conservation efforts on these farms have traditionally focused on planting exotic tree and shrub species, such as spaced poplar, willow, and radiata pine (McIvor et al. 2011). However, there is growing interest in using native woody species as alternative for stabilising steep slopes (Phillips et al. 2015). Despite this interest, limited information is available on how native species compare to exotic ones in terms of effectiveness in stabilising the steep slopes and impacts on farm economics.

Radiata pine is widely utilised compared to other exotic tree and shrub species for soil conservation on hill country sheep and beef farms because of its fast growth rate, broad site tolerance, and potential for higher economic returns from log sales (Satchell 2018). The fast growth rate of radiata pine makes it superior for carbon sequestration and in stabilising soil on the steep slope (Ministry for Primary Industries 2017). Additionally, radiata pine has shorter harvesting rotation which makes it the dominant forestry species accounting for over 90% of log production in New Zealand (Satchell 2018). However, the monocultural plantation of radiata pine can reduce biodiversity, and the short harvesting rotations expose steep slopes to cyclical vulnerability to soil mass movement (Phillips et al. 2015). This practice can increase the storm-induced risk of slash (wood debris) washing into waterways after harvesting, potentially causing significant damage to properties, infrastructure, the environment, and aquatic ecosystems (Phillips et al. 2015; Satchell 2018). Additionally, the roots of radiata pine decay rapidly after tree harvesting, which diminishes soil stability and increases the risk of soil mass movement on steep slopes (Phillips et al. 2015; Satchell 2018).

New Zealand has more than 2,000 native plant species (Ministry for the Environment & Stats NZ 2018), with nearly 85% endemic to the country (Kerr and Stewart 2014). Over 400 of these native species are shrubs and cover approximately 10–15% of the country land mass (Allen et al. 2013; Norton and Pannell 2018). Approximately 17% of this native woody vegetation is on hill country sheep and beef farms steep slopes (Beef +Lamb NZ 2018, 2022a; Norton and Pannell 2018). Native shrubs have a myriad of uses because of their taxonomic diversity. Socially, some native shrubs have cultural values and others are used for crafts, ethnomedicine, and as ornamental plants (Brooker et al. 1989). Ecologically, they provide habitat to wildlife and act as nursing plants to higher canopy flora (MacGibbon 2014). Their diverse growth forms and adaptability to various ecological niches make them valuable for landscape restoration and aesthetics (Dodd and Ritchie 2007). In addition, some native shrubs are preferred and browsed by wild herbivores (Bee et al. 2011), making them a potential source of forage to the farmed ruminants. Studies on the nutritional composition of some browsable native shrubs indicate that they can offer superior metabolisable energy compared to summer pasture, although they are generally lower in crude protein (Simmonds 2020; Wangui et al. 2022). Environmentally, native shrubs provide continuous ground cover and soil reinforcement for longer periods than commodity trees with determined harvest cycles (Hawke's Bay Regional Council 2004). Further, native shrubs are significant carbon sinks and can provide supplementary income through carbon trade if established on the farm (Ministry for Primary Industries 2017; Kimberley et al. 2021; Wangui et al. 2021).

An earlier simulation modelling study found that utilisation of native shrubs as an alternative land use to pasture on hill country farms' steep slopes are economically viable at carbon prices above 56 NZD/ NZU (Wangui et al. 2021). A New Zealand Unit (NZU) is equal to a tonne of carbon dioxide equivalent (Ministry for Primary Industries 2017). The model consisted of a hill country sheep and beef farm base model (Farrell 2020) to which a native shrub sub-model was added (Wangui et al. 2021). However, the native shrubs sub-model was based on limited literature data (Wangui et al. 2021). Therefore, part of this study aimed to update the native shrubs sub-model using new research findings. Additionally, a radiata pine sub-model was developed and integrated into the overall model, allowing for a comparison between radiata pine and native shrubs as alternative land use options to pasture on hill country farms. Consequently, the objective of this study was to utilise the improved model to compare the impacts of asynchronous use of either native shrubs or radiata pine on (1) farm feed supply, (2) sheep flock dynamics, and (3) farm economics, focusing on 10% of the effective farm area on the steep slope portion.

Methods

Model development and structure

A Radiata Pine subsystem model (RPM) was developed in STELLA Architect (Version 3.7 [3335]; isee Systems, Lebanon, NH, USA) and integrated into the New Zealand North Island hill country sheep and beef farm model (HCM) (Farrell et al. 2019), which was previously improved to include a Native Shrubs subsystem Model (NSM) (Figure 1) (Wangui et al. 2021). The HCM was organised into modules representing sheep flock, beef cattle herd, pasture feed utilisation, wool production and farm economics (Farrell et al. 2019). Simulations of HCM have been used to assess the impacts of sheep wastage rates on the productivity and profitability (Farrell et al. 2019), sheep flock replacements (Farrell, Kenyon, et al. 2020), sheep breeding strategies (Farrell, Morris, et al. 2020) and beef herd management (Farrell, Morris, et al., 2020; Farrell, Tozer, et al. 2020; Farrell et al., 2021) of hill country sheep and beef farms. The addition of NSM to HCM allowed for partitioning of the hill country sheep and beef farm into three (flat, medium, and steep slopes) land use classes and allocation of native shrubs to a portion of the steep slope. The NSM consisted of native shrubs growth, fodder supply, carbon stock and shrub economics

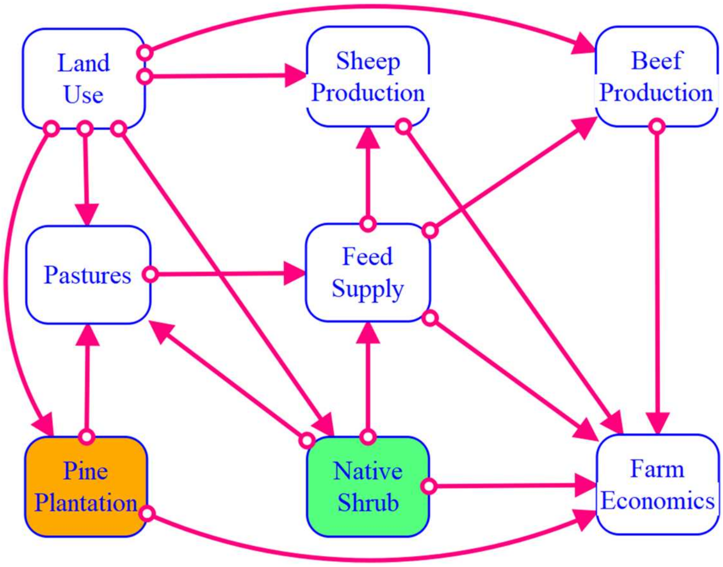

Figure 1. Schematic diagram of the modules of the hill country sheep and beef farm model (HCM) (white fill) (Farrell 2020), native shrub (NSM) subsystem model (green fill) (Wangui et al. 2021) and the radiata pine subsystem model (brown fill). The arrows show the direction of interaction among the modules and subsystem models.

modules (Wangui et al. 2021). System dynamics of HCM and NSM are detailed in Farrell et al. (2019), Farrell (2020) and Wangui et al. (2021), respectively.

The Native Shrub Model (NSM) initially assumed that native shrubs were the sole alternative to pasture for use on steep slopes (Wangui et al. 2021). However, other trees and shrub species are also planted on the steep slope for various purposes including soil conservation, landscape restoration, windbreaks and wood production (Satchell 2018). Among these alternatives is radiata pine (Satchell 2018). To facilitate the asynchronous use of native shrubs and radiata pine on steep slopes, the Radiata Pine Model (RPM) was developed. The RPM consisted of radiata pine growth, wood production, carbon stock and radiata pine economics modules. Both the NSM and the RPM represented afforestation interventions, while the use of pasture on steep slopes served as the baseline scenario.

The baseline (pasture) and afforestation interventions scenarios were simulated over a 50-year period. The base scenario simulated the farm with pasture production grazed by livestock (sheep and beef cattle) on all the slope classes. Afforestation interventions scenarios considered using either the native shrubs or radiata pine on the farm steep slope. Both native shrubs and radiata pine provided carbon trade income to the farm cashflow, but radiata pine had extra income from sale of logs. Additionally, native shrubs were assumed to contribute browse fodder and understorey pasture to the farm feed supply during the browsing period.

Characteristic of the modelled farm

The model simulated an average class 4 North Island hill country sheep and beef farm located on the East Coast region in New Zealand. The location was used because it was the base region for HCM (Farrell et al. 2019) previous simulations and (Wangui et al. 2021). In addition, this region accounts for approximately 50% of the North Island sheep population (Beef+Lamb NZ 2022a, 2022c), has greater proportion of steep slopes (Marden, Fuller, et al. 2018) with some portions planted in radiata pine (Satchell 2018). The average farm effective area in the East Coast region is approximately 624 ha (Beef+Lamb NZ 2022b), of which approximately 50% is steep slopes (Saggar et al. 2015). Slope proportions of 8.7% flat, 45.9% medium and 45.4% steep slopes were used in the model to mimic an average hill country farm in the region (Wangui et al. 2021). The slope classes proportions were within the ranges of those found on the East Coast region hill country farms (Saggar et al. 2015).

Studies of hill country farms have often used different slopes elevations to classify the slope classes (Saggar et al. 2015; Kemp and Lopez 2016; Beef+Lamb NZ 2020c). However, the model adapted elevation of <12° for flat, 13–25° medium and >25° for steep slope (López et al. 2003) to reflect the slopes critical to pasture production (Lynn et al. 2009). Slope classes differ in microclimate and soil properties, which affects pasture yield and quality (López et al. 2003). Flat areas on the hill country farms have higher pasture production and quality; pasture production reduces with increasing slope elevation (Kemp and Lopez 2016). As a result, flat to medium slopes have a relatively high carrying capacity of up to 13 stock units (SU) per ha, while steep slopes supports fewer than 7 SU per ha (Beef+Lamb NZ 2022b). A SU in New Zealand represents the annual feed a 55 kg ewe rearing a single lamb to weaning at 28 kg requires (Lynn et al. 2009).

Sheep flock and beef herd dynamics

The current model retained the livestock classes and structure in HCM (Farrell et al. 2019) and the sheep flock dynamics in NSM (Wangui et al. 2021). The beef cattle herd was maintained at a constant size, receiving 40% of the farm feed supply (Beef+Lamb NZ 2022b) and was similar to the earlier studies using the model (Farrell 2020; Wangui et al. 2021). However, the sheep flock fluctuated in response to feed supply dynamics caused by land use changes on steep slopes (Wangui et al. 2021). Changes in land use from pasture to afforestation can affect the farm feed supply and hence the SU supported by the farm (Satchell 2018). As such, the model maintained a self-adjusting sheep flock that responded to available feed supply at the beginning of each year (Wangui et al. 2021) with no external sourcing of feed and replacement flock (Farrell et al. 2019). To maintain a stable sheep flock, reduction in feed supply led to more ewe lambs sold while increased feed supply allowed for increased numbers of lambs sold prime for slaughter (Wangui et al. 2021). Sheep flock management on reproduction, culling and deaths for all age groups (Farrell et al. 2019) were adjusted to reflect the production status of a hill country sheep and beef farm on the East Coast region for the year 2020–2021 (Beef+Lamb NZ 2022b).

Land use on the modelled farm

Land use was grouped into four areas based on the slope classes (flat, medium, and steep slopes) and their utilisation. Flat and medium slopes were entirely used for pasture production. However, the steep slope was divided into pasture and afforestation areas. The afforestation area covered 10% of the total effective farm area (62.4 hectares) and was planted with either native shrubs or radiata pine. The remaining non-afforested steep areas were kept as pasture. Monthly pasture production and quality data for the East Coast region (Farm Technical Manual, 2011) was used as the average for flat land, as pasture yield and quality vary across different slope classes (Lambert et al. 2014; Kemp and Lopez 2016). Modelled pasture production for the medium and steep slopes was adjusted to be approximately 52.6% and 38.6% of the flat land production. The adjusted pasture production for the slope classes was within the reported range for North Island and the East Coast region (Lambert et al. 2014; Kemp and Lopez 2016).

Management of the afforestation site

Prior to planting with either native shrubs or radiata pines, the steep slopes contained unimproved pasture and were used for grazing. Site preparation for afforestation with either native shrubs or radiata pine was similar and involved weed control and fencing. Weed control and fencing were carried out only on the area to be planted in each year. Aerial non-selective herbicide application was used to control brush weeds due to limitation of using other mechanised methods on the steep slope. Fencing was carried out to demarcate the area for afforestation in each year and to control sheep and beef cattle from damaging the seedlings and consuming the native shrubs.

Seedlings were assumed to be sourced locally and transported to the planting site. Containerised and bare rooted seedlings were used for native shrubs and radiata pine (Cimino et al. 2014). Seedlings were hand planted for both the native shrubs and radiata pine(Maclaren 1993; Cimino et al. 2014). During planting, diammonium phosphate (DAP) fertilizer was applied (approximately 85 g per seedling) to support seedlings root development (Davis et al. 2010). Pest control using a trap per hectare was used to control pests immediately after planting (Brown 2020). Post planting management of the afforestation site was similar for the native shrubs and radiata pine and involved fence maintenance and weed control. Fence maintenance was carried out annually starting a year after installation for the simulation and rotation period for native shrubs and radiata pine, respectively. Only a single subsequent weed control was carried out two years after planting to suppress competition from weeds. The costs for establishing the seedlings and post planting management were obtained from (Lincoln University 2021)

Estimation of native shrubs growth

Plant growth exhibits a sigmoid growth curve and can be described using nonlinear mathematical functions (Paine et al. 2012). Among these, the Gompertz function is widely used to estimate plant growth because it accounts for variable growth rates and has an asymmetrical shape (Paine et al. 2012). In this study, we applied the Gompertz function (Equation 1) to estimate the basal stem diameter growth of native shrubs over a 50-year period. The function parameters were derived by fitting the measured basal diameters of three native shrub species: *Coprosma robusta* (Karamū), *Pittosporum crassifolium* (Karo), and *Melicytus ramiflorus* (Māhoe) (Figure 2). Data were collected from 54 shrubs including *C. robusta* ($n = 18$), *P. crassifolium* ($n = 19$), and

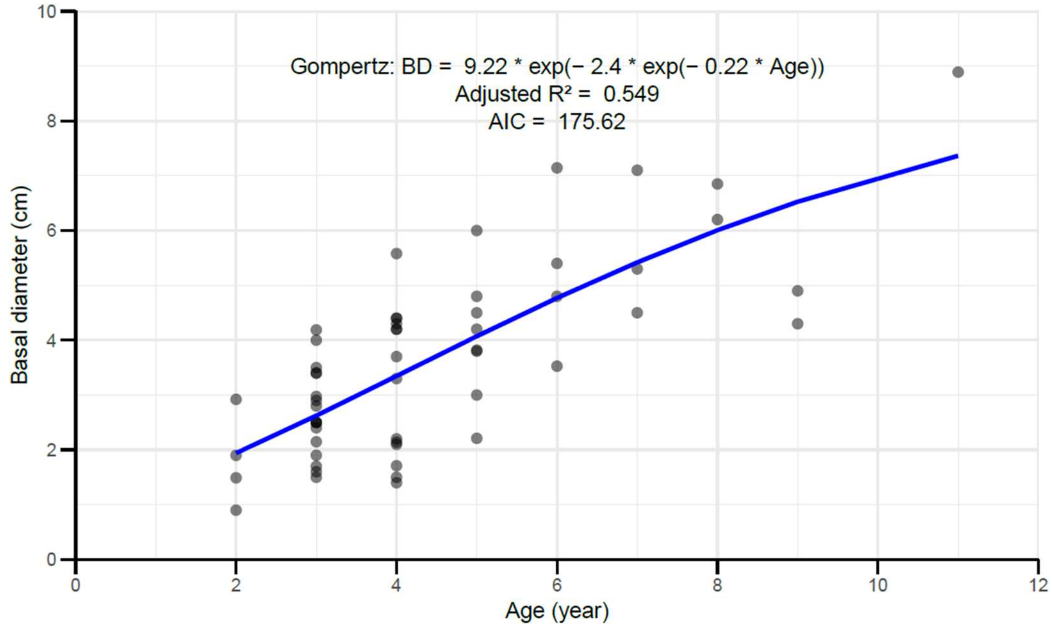

Figure 2. Gompertz curve with estimated parameters illustrating the relationship between age and stem basal diameter for mixed native New Zealand shrubs: *Coprosma robusta* (Karamū), *Pittosporum crassifolium* (Karo), and *Melicytus ramiflorus* (Māhoe).

M. ramiflorus (17) aged between 2 and 11 years. The native shrubs were sampled from natural reserves located in Palmerston North and Waikato and a trial site at Massey University's Dairy 4 farm.

$$BD_i = 9.22 \times \exp(-2.4 \times \exp(-0.22 \times Age)), \tag{1}$$

where BD_i represents the estimated native shrubs stem basal diameter. The native shrubs sample was intended to represent mixed shrubs across different geographical areas. The native shrubs sampled in this study from the natural reserve was assumed to have a mixed plant density of approximately 8,500 stems per hectare (sph). Previous studies reported densities ranging from 1,000 to 10,000 sph (Bergin and Kimberley 2014; Cimino et al. 2014; Kimberley et al. 2014). Higher densities, exceeding 10,000 sph, typically lead to early canopy closure within about three years, while lower densities, under 1,000 sph can delay canopy closure for more than 10 years (Bergin and Kimberley 2014). A planting density of around 2,500 sph (2-meter spacing) is generally recommended for achieving canopy closure approximately 10 years after planting (Bergin and Kimberley 2014). For the model in this study, an initial density of 2,000 sph was used. This planting density allows for successful shrub establishment within five years and permits browsing for the next five years before canopy closure, which is expected to occur around 10 years after planting (Bergin and Kimberley 2014).

Estimation of native shrubs foliage yield and nutritional quality

Plant growth involves the simultaneous increase in size of various components, including roots, stems, branches, leaves, and reproductive tissues. This growth relationship can be effectively modelled using allometric functions (Marden, Lambie, et al. 2018). The allometric relationship between stem diameter and foliage yield is well established (De Cáceres et al. 2019; Sun et al. 2019) and can be used to estimate fodder production in trees and shrubs (Poorter et al. 2015). However, growth rates can vary by species and allometric functions can differ across genera (Poorter et al. 2012). Despite this variability, generalised allometric functions based on stem basal diameter have proven effective in estimating foliage yield for mixed shrub species (He et al. 2018; Flade et al. 2020). In this study, foliage biomass estimated from the native shrubs in the section 'Estimation of native shrubs growth' was related to the BD and used to develop a generalised allometric function (Equation 2) to estimate the potential foliage yield from a mixed stand of native shrubs. Foliage was defined as the edible parts for sheep, including leaves and soft branchlets less than 5 mm in diameter (Kemp et al. 2003).

$$F = 0.013 \times BD^{1.96}, \tag{2}$$

Where F represented the foliage yield (dry matter).

Variations in nutritional composition between species is primarily influenced by phylogenetic factors, while seasonal differences are driven by changes in weather and soil conditions (Wangui et al., 2024). Native shrub nutritional composition differences are more pronounced in leaves than in their edible stems (Wangui et al. 2022, 2024). In this study, it was assumed that sheep browse on both leaves and edible stems in equal proportions. As a result, the overall foliage quality was calculated as the average nutritional quality of the leaves and edible stems, measured in terms of metabolisable energy (ME). The monthly foliage quality (Figure 3) was estimated based on the seasonal average ME values of five native shrub species (Wangui et al. 2022, 2024).

Feed supply with native shrubs planted on the farm.

The feed supply in the modelled farm comprised of pasture and native shrub fodder and was expressed in megajoules of metabolisable energy (MJ ME) (Wangui et al. 2021). Pasture supply was from both open and understory pasture. Open pasture was from flat and medium slopes and non-afforested area on the steep slope, while understory pasture formed the ground cover on the afforested area in native shrubs. Open pasture was available for grazing to both beef cattle and sheep throughout the simulation period. However, native shrub fodder and understory pasture were allocated to sheep and available only during the browsing period (summer season) for a period of five years. The allocation of native shrub fodder and understory pasture to sheep was because sheep can browse the shrubs with minimal damage and exert a lower trampling impact compared to beef cattle.

The browsing period occurred between the fifth and tenth year after planting the native shrubs. The first five years after planting allowed the native shrubs to establish and attain enough growth to withstand periodical browsing (Cimino et al. 2014; Marden, Lambie, et al. 2018). Withdrawal of browsing 10 years after planting the native shrubs was because at this age canopy closure was assumed to be above 65%, which can limit sheep access and restrict understory pasture growth (Bergin and Kimberley 2014). Further, native shrubs older than 10 years can have browse heights beyond the reach of the sheep, which is approximately 1.2 m (Sanon et al. 2007). Sheep were assumed

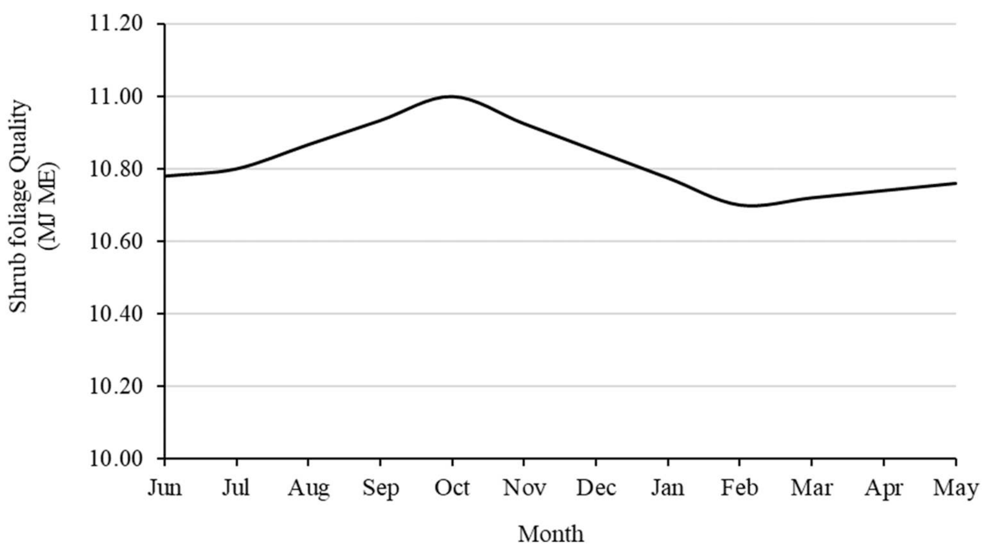

Figure 3. Estimated monthly foliage quality in mega Joules of metabolisable energy (ME MJ) for mixed native shrub (*Coprosma robusta, Griselinia littoralis, Hoheria populnea, Pittosporum crassifolium* and *Pseudopanax arboreus*) endemic to New Zealand (Wangui et al. 2022, 2024).

to browse native shrubs fully up to the height of approximately 0.9 m (Sanon et al. 2007; McEvoy and McAdam 2008), beyond which fodder access declined logarithmically and ceased at 5 m due to self-pruning caused by canopy closure (Wangui et al. 2021). Similarly, understory pasture growth rates decreased logarithmically with growth of native shrubs due to the shading effect (Wangui et al. 2021). The estimation of feed supply from afforested areas in native shrubs using NSM was retained (Wangui et al. 2021).

Feed demand was estimated based on sheep flock and beef cattle herd feed requirements for each year (Farrell et al. 2019). The difference between feed supply and demand was taken as the feed balance for the farm (Farrell et al. 2019) and was used to estimate sheep flock self-adjustments (Wangui et al. 2021).

Pine radiata use on the steep slopes

Radiata pine is the most planted forest species and is used as a bench mark for comparing other species in New Zealand forestry (Satchell 2018). It is a timber commodity species with no fodder use (Satchell 2018) and therefore must be harvested for logs within 25–35 years of growth for it to be economically feasible (Satchell 2018). The RPM simulated radiata pine growth in terms of log production and carbon stock accumulation over a rotation length of 25 years (Satchell 2018). An initial planting density of 1,000 sph was used with the trees thinned to a final log production stand of approximately 500 sph (NZ Farm Forestry 2007). Two non-production thinnings were carried out in the 7th and 12th years of the rotation (Maclaren 1993). To ensure clearwood logs of good quality trees were pruned in three lifts (Maclaren 1993; NZ Farm Forestry 2007). A sail prune was carried out at the 3rd year to remove double leaders, a clear lift to 10 cm trunk at the 5th year and a final lift to the target height of 6.5 m at the 8th year (NZ Farm Forestry 2007). Logs harvesting was carried out using cable logging because of the steep nature of the afforested area (Maclaren 1993). Recoverable log in cubic meters (m^3) for each grade were estimated using the yield tables for a post 1989 radiata pine plantation on the East coast region (Ministry for Primary Industries 2022). Carbon stock accumulation for the rotation period and residual carbon stock after harvesting were estimated using the pre-calculated values for post 1989 radiata pine plantation on the East coast region (Ministry for Primary Industries 2017; Kiro 2022).

Carbon stock and sequestered carbon dioxide estimation

The accumulated carbon stock in the plant biomass can be expressed in terms of the carbon dioxide sequestered as the plant grows and for a specific area. Carbon stock expressed in tonnes of carbon dioxide per hectare (t CO_2 ha^{-1}) for some common New Zealand forestry species have been estimated by age (Ministry for Primary Industries 2017). Precalculated values of t CO_2 ha^{-1} for radiata pine forest planted post 1989 in Hawkes Bay (Ministry for Primary Industries 2017) were used to simulate carbon stock accumulation for the species. Unlike radiata pine, regional estimates of t CO_2 ha^{-1} for mixed native shrubs have not been documented (Kimberley et al. 2021), largely because of their wide genetic diversity (Metcalf 2011), except for generalised estimates using manuka/kanuka shrubs (Ministry for Primary Industries 2017). In this study, the carbon stock for mixed native shrubs was estimated using dry biomass data for the above ground biomass components (foliage, branches and stem) obtained for the shrubs used in the section ‘estimation of native shrubs growth’. The total above ground biomass (AGB) was estimated using a seemingly unrelated regression (SUR) model encompassing the foliage (fBM), branches (bBM) and stem biomass (sBM) (Equation 3). Earlier studies have estimated that AGB accounts for between 65 and 75% of the total biomass (TBM) in native shrubs (Marden, Fuller, et al 2018; Marden, Lambie, et al. 2018). Since below ground biomass (BGB) for the sampled shrubs was not measured in this study, it was assumed to be around 33% of the AGB, with the total biomass (TBM) estimated as 1.33 times the AGB. The carbon stock was assumed to be approximately 50% of the TBM (Beets et al. 2014). The estimated carbon content was then multiplied by the molecular weight ratio (3.67) of carbon dioxide (CO_2) to carbon to calculate the sequestered CO_2 stock (Kimberley et al. 2014; Easdale et al. 2018).

$$\mathrm{AGB} = \mathrm{fBM} + \mathrm{bBM} + \mathrm{sBM}, \tag{3}$$

where

$$\begin{aligned} \mathrm{fBM} &= 0.013 \times \mathrm{BD}^{1.96}, \\ \mathrm{bBM} &= 0.007 \times \mathrm{BD}^{1.54} \times \mathrm{H}^{1.38}, \\ \mathrm{sBM} &= 0.017 \times \mathrm{BD}^{1.94} \times \mathrm{H}^{0.66}, \end{aligned}$$

and H represents the native shrubs height.

The averaging accounting method (Kiro 2022) was used for carbon trading for both native shrubs and radiata pine in the present model. The averaging accounting method was used because the model assumed afforestation of the steep slope was carried out after the beginning of the year 2023 when the requirement was enforced (Kiro 2022). The stock change accounting method allowed for periodic (5 years) carbon trading as the forest grows and surrendering of released carbon after trees or shrubs are harvested (Ministry for Primary Industries 2017). However, the average accounting method uses the estimated long-term average carbon stock accumulation that a given forest type can sequester and allows carbon trading up to the age the forest attains the long-term averaged carbon stock (Kiro 2022). Unlike in the stock change accounting method, carbon released from harvested forest in averaging accounting method is not surrendered if the harvesting was carried out after attaining the age estimated for long -term average carbon and the area is reafforested (Kiro 2022). The typical average age for radiata pine and native shrubs to attain long-term average carbon used was 16 and 23 years, respectively (Kiro 2022).

Farm economic analysis

The total farm cashflow comprised of income and operating expenses from the beef herd, sheep flock, native shrubs or radiata pine enterprises. Beef herd remained constant during the simulations (Farrell et al. 2019) and was unaffected by land use changes (Wangui et al. 2021). Cash flow for the sheep enterprise depended on flock size and lamb sale policy, both influenced by feed supply (Farrell, Kenyon, et al. 2020).

Consequently, sheep enterprise cash flow was impacted by land use changes on steep slopes, afforestation species, and planting rates. In contrast, cash flow for native shrubs and radiata pine was affected solely by planting rates.

Economic assessment was carried out at three discount rates 5, 7 and 10%. A 7% discount rate is the recommended estimate for cost benefit evaluation of investments in the public sector in New Zealand (The Treasury 2008). Discount rate of 5 and 10% were applied to consider lower and higher risk scenarios, respectively, due to uncertainties about future inflation (The Treasury 2008). The assessment utilised several economic tools, including discounted net cash flow in terms of cash operating surplus (COS), net present value (NPV), and break-even analysis (BA) (Wangui et al. 2021).

The afforestation interventions were compared to a base scenario with pasture on the farm steep slopes. Afforestation scenarios involved use of either native shrubs (NS) or radiata pine (RP) at two planting rates 10% and 20%. A planting rate of 10% implied, the afforestation area was split into 10 equal portions and a 10% planted annually. The economic assessment used outputs from five simulations: no afforestation, 10% NS, 20% NS, 10% RP, and 20% RP.

Cash flow calculations for the beef herd and sheep flock enterprises followed the HCM model (Farrell et al. 2019) while calculations for native shrubs followed the NSM model (Wangui et al. 2021). The income and expenses for HCM and NSM were updated to reflect the present production status in hill country sheep and beef farms on New Zealand East Coast region (Beef+Lamb NZ 2022b). Radiata pine expenses included the cost of land preparation, planting, post-planting management, harvesting and marketing costs, while cash inflow was from carbon trade and sale of logs (Maclaren 1993). Due to the steep terrain, thinning, pruning, and logging costs were adjusted to be 15% higher than on easier slopes (Lincoln University 2021). Carbon income was estimated using three-year (2020–2023) average carbon price of 55.6 NZD/NZU. Log sale income was based on the average price over 12 quarters ending in December 2022 for different log classes (pruned, A grade, K grade, and pulp) for export(Ministry for Primary Industries 2023).

The capital for establishing native shrubs and radiata pine on the steep slopes was assumed to come from farm proceeds. The net cash flow, expressed as cash operating surplus (COS), focused on the sheep enterprise, as afforestation primarily affected sheep production. The sheep enterprise COS consisted of three components: (a) the sheep flock, (b) native shrubs, and (c) radiata pine net cash flows. In the base scenario pasture (without afforestation), the sheep enterprise COS included only the sheep flock net cash flow. In the afforestation scenarios, the COS included the sheep flock net cash flow plus additional net cash flows from either native shrubs or radiata pine. Additionally, the economic analysis compared the net present value (NPV) of the sheep enterprise for flock on pasture to scenarios with native shrubs or radiata pine at planting rates of 10% and 20%. The three discount rates (5%, 7%, and 10%) were applied to account for future inflation uncertainties. A break-even analysis determined the carbon price per New Zealand Unit (NZD/NZU) required to equalise the COS for the sheep enterprise with afforestation interventions to that based on pasture. One NZU is equivalent to one metric tonne of carbon dioxide equivalent.

Results and discussion

Farm feed supply

Overall farm feed supply

Annual farm feed supply with pasture on the steep slope was 25.9 million MJ ME and remained constant over the simulation period (50 years) (Figure 4). This was an 11.5% increase in total farm feed supply (23.23 million MJ ME) compared to the previous model (Wangui et al. 2021). The increase was due to 10.6% increase in the effective farm area in the current modelled farm (624 ha) (Beef+Lamb NZ 2022b) as compared to previously modelled farm (564 ha) due to changes in the benchmarking data used in the previous model (Beef+Lamb NZ 2020b).

The long-term average annual feed supply on the farm decreased after 62.4 hectares of steep slopes were converted from pasture to afforestation. The reduction can be expected because withdrawal of pasture area from grazing led to a decrease in feed supply from the steep slopes. The decrease in feed supply ranged from 2.5 to 4.0% with native shrubs, and from 7.0 to 7.4% with radiata pine, at planting rates of 10% and 20%, respectively. Notably, the reduction in feed supply (4.0–7.4%) was smaller than the proportion of farm area (10%) withdrawn from grazing. This suggests that converting steep pasture to woody vegetation has a limited impact on the farm carrying capacity.

Feed supply from the slope classes

The total annual feed supply from the flat (4,480,928 MJ ME) and rolling (12,435,039 MJ ME) slope classes remained constant throughout the simulation period (Table 1). When

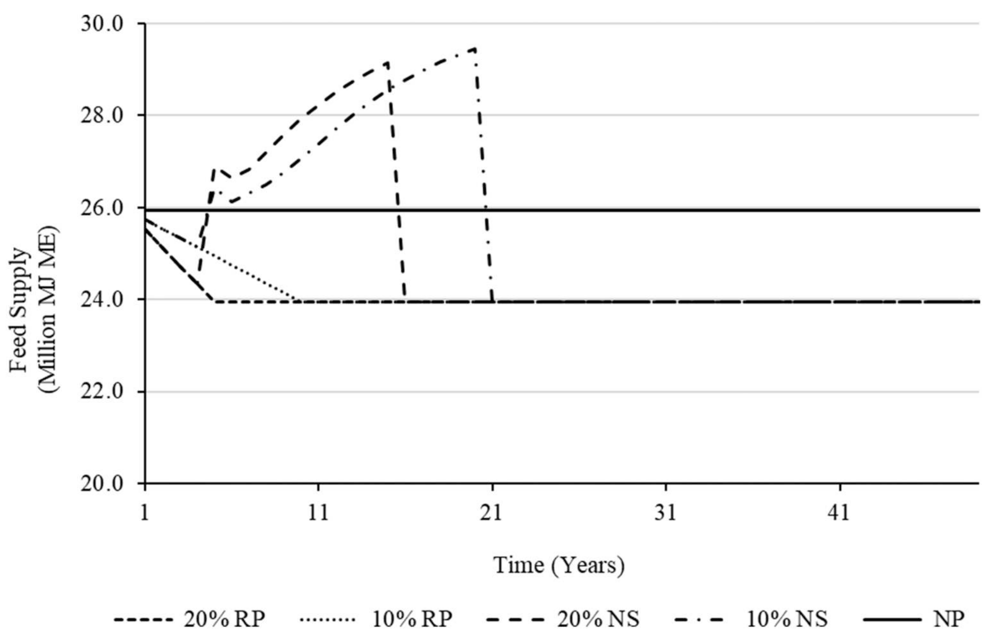

Figure 4. Annual total farm feed supply in megajoules of metabolisable energy (MJ ME) over 50 years for an area equal to 10% of the farm effective area on the steep slope with pasture (NP) or planted in native shrubs (NS) or radiata pine (RP) at two planting rates (10% and 20% per year).

Table 1. Modelled farm mean annual feed supply in megajoules of metabolizable energy (MJ ME) for the flat, rolling and steep slope classes with pasture and with native shrubs or radiata pine planted on the steep slope on an area equal to 10% of the effective farm area (624 ha) at two planting rates (10% and 20%) and the proportion (%) of total feed allocated to sheep flock.

Planting rate	Land use	Slope class feed supply (MJ ME)			Total farm feed (MJ ME)	Sheep feed (%)
		Flat	Rolling	Steep		
0%	Pasture	4,480,928	12,435,039	9,025,929	25,941,896	60.0
10%	Native shrub	4,480,928	12,435,039	8,389,933	25,305,900	58.5
	Radiata pine	4,480,928	12,435,039	7,216,767	24,132,734	55.8
20%	Native shrub	4,480,928	12,435,039	7,980,811	24,896,778	57.6
	Radiata pine	4,480,928	12,435,039	7,117,362	24,033,329	55.6

Note: The remaining feed supply after sheep allocation is allotted to beef cattle integrated into the farm.

converted to dry matter per hectare per year basis, flat (11,790 kg DM/ha/y) and rolling (6,200 kg DM/ha/y) slopes pasture production was within the ranges reported for the hill country sheep and beef farms (Praat 2011; Lambert et al. 2014; Kemp and Lopez 2016). Converting 62.4 ha of steep slopes from pasture to either native shrubs or radiata pine reduced feed supply, with radiata pine causing greater reductions (21.2% and 20.0%) than native shrubs (11.6% and 7.0%) at 20% and 10% planting rates, respectively. The greater reduction with radiata pine occurred because afforested areas were not used for browsing or understory grazing, unlike areas with native shrubs. The larger reduction at the 20% planting rate resulted from the withdrawal of 12.8 ha over 5 years, compared to 6.4 ha over 10 years for the 10% rate. On average, feed supply on steep slopes was 16.3% and 12.1% higher with native shrubs than with radiata pine at 10% and 20% planting rates, respectively. This indicates that native shrubs contributed significantly to farm feed supply, primarily due to their use for browsing during the summer season. The overall reduction in feed supply led to a proportionate decrease in feed allocated to the sheep flock.

Feed supply from the area planted in native shrubs on the steep slope

The total feed supply over the browsing period was more for native shrubs at 10% planting rate (58 million MJ ME) than at 20% planting rate (43 million MJ ME) (Figure 5). Although higher, this agrees with earlier findings and can be attributed to the longer browsing period for the 10% than the 20% planting rate (Wangui et al. 2021). Although the area planted annually at 10% was half that at the 20% planting rate, multiple overlapping portions were available for browsing and understory grazing resulting in cumulatively more feed supply for the 10% planting rate. However, the mean annual feed supply over the browsing period was 7.5% more at the 20% planting rate (3.9 million MJ ME) than at 10% planting rate (3.7 million MJ ME). The higher mean annual feed supply at 20% would be expected because a large portion (12.48ha) was available for browsing and understory grazing annually and therefore more feed supply was available over the shorter browsing period (10 years).

Sheep flock size and structure dynamics

Effects of using native shrubs or radiata pine on flock size

The sheep flock size for the modelled farm with pasture on the steep slope was 3,055 and was maintained constant over the simulation period. The current modelled farm flock

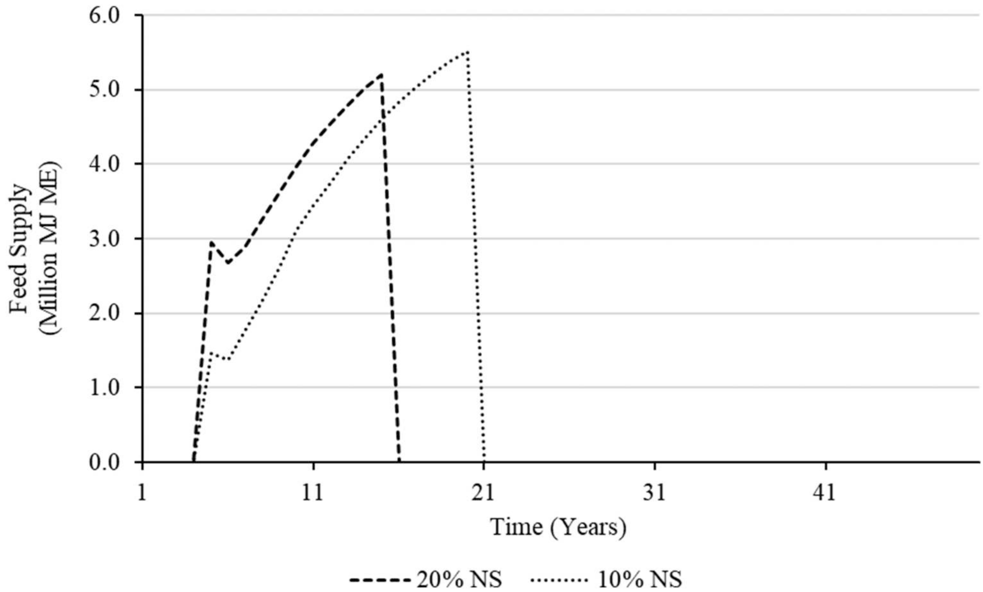

Figure 5. Annual feed supply megajoules of metabolisable energy (MJ ME) over 50 years from the steep slope portion (10% of farm effective area) planted in native shrubs (NS) at two planting rates (10% and 20% per year).

was 11.2% larger than in the previous model (2,747) (Wangui et al. 2021) and matched the proportionate increase in the effective farm area. The flock structure was similar in the two models and comprised 70% ewe, 20% replacement flock, and 10% other sheep. However, the current model flock size was 5.7% lower than the estimated mean flock size (3,231) for a class 4 hill country sheep and beef farm in the East Coast region for the year ending 2021 (Beef+Lamb NZ 2022b). The difference was because the current model mimicked an individual farm, while (Beef+Lamb NZ 2022b) estimates were based on the mean of the farms which can vary in farm characteristics, management and flock sizes (Beef+Lamb NZ 2022b). Nonetheless, the ewe flock size (2,413) in the current model was similar to the estimates by Beef+Lamb NZ (2022b).

As expected, the decrease in farm feed supply led to a reduction in the overall mean annual flock size. The reduction was more pronounced with radiata pine (12.1% and 11.4%) than with native shrubs (6.5% and 3.9%) and was greater at the 20% planting rate compared to the 10% rate. The difference in flock size reduction between native shrubs and radiata pine is due to native shrubs providing some browse and understory feed during the browsing period, temporarily increasing the farm's carrying capacity (Figure 6). The larger flock reduction at the 20% planting rate resulted from the greater decline in feed supply and the need for larger flock adjustments to accommodate the change.

Effects of using native shrubs or radiata pine on flock structure dynamics

Fluctuations in farm feed supply led to adjustments in the flock structure (Table 2). Reduction in the farm feed supply during the planting stage of the native shrubs and radiata pine resulted in more lambs being sold, which caused a reduction in the

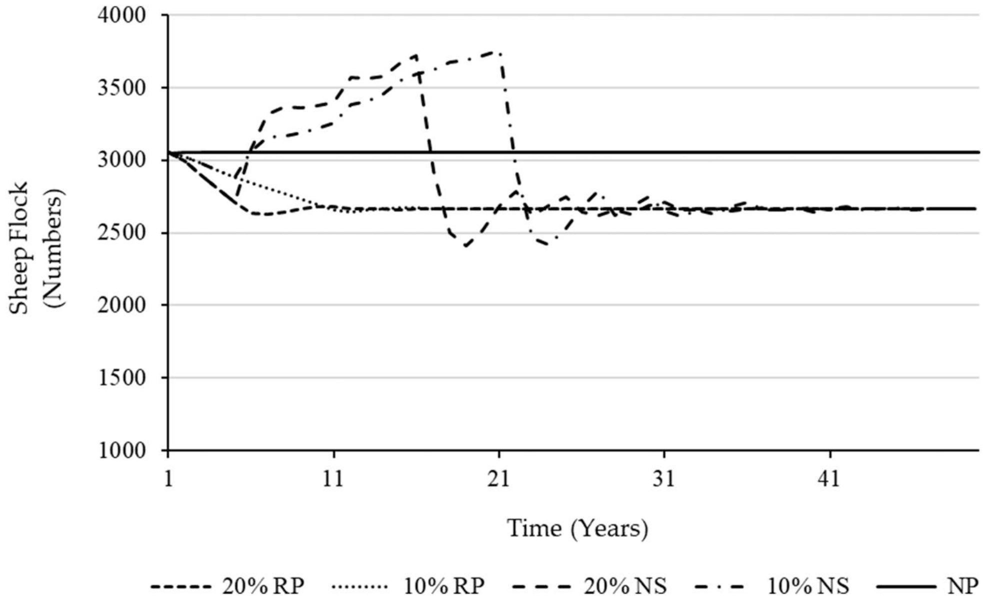

Figure 6. Annual sheep flock size over 50 years for the modelled farm with pastures (NP) or planted in native shrubs (NS) or radiata pine (RP) on an area equal to 10% of the effective farm area on the steep slope at two planting rates (10% and 20%).

replacement flock entering the ewe flock. Subsequently, reduction of replacement flock led to a decrease in the number of ewes across the age classes resulting in a greater reduction of the ewe flock size. Preference of using lambs over mature ewes in manipulation of the flock size was because the replacement youngstock maintains the flock structure stability (Farrell, Kenyon, et al. 2020). In addition, adjusting the replacement flock instead of culling mature ewes maintains the ewe flock reproductive performance which peaks at five years (Farrell et al., 2019; Farrell, Kenyon, et al. 2020).

Net cashflow and farm economics

The net cash flows for the sheep flock on pasture and with native shrubs, or radiata pine are presented first and then the sheep enterprise COS for each of the scenarios explored. In the base scenario, the sheep enterprise COS consisted solely of the net cash flow from the sheep flock. In the afforestation scenarios, the sheep enterprise COS included the net cash flow from the sheep flock, along with additional net cash flows from either native shrubs or radiata pine.

Table 2. Sheep flock size changes from the base scenario across the flock structure in percentage over 50 years for the modelled farm planted in native shrubs (NS) or radiata pine (RP) on an area equal to 10% of the effective farm area (624 ha) on the steep slope at two planting rates (10% and 20%).

		Native shrubs		Radiata pine	
Flock structure	Flock size	10%	20%	10%	20%
Sheep flock	3055	−3.9	−6.5	−11.4	−12.1
Ewe flock	2413	−3.7	−6.3	−11.3	−12.0
Replacement flock	605	−4.7	−7.3	−12.1	−12.7

Sheep flock cashflow

The net cash flow for the sheep flock using the base scenario showed a smooth, exponential decrease over the simulation period, reflecting the impact of the discount rate on the constant future cash flows (Figure 7). However, when steep slope land use shifted from pasture to either native shrubs (Figure 7a) or radiata pine (Figure 7b), fluctuations in feed supply affected flock size. This in turn impacted on the number of lambs sold and therefore the flock cash flow. During the planting stage of both native shrubs and radiata pine, portions of pasture were withdrawn from grazing, leading to a reduction in flock size to balance feed supply with demand. As discussed in the section 'Effects of using native shrubs or radiata pine on flock size', this flock reduction was primarily achieved by increasing lamb sales, which temporarily increased the net cash flow during the afforestation interventions. Once planting was completed, the afforested areas were no longer available for grazing, meaning the farm had to reduce the flock size to balance the feed demand with supply. The reduced flock size resulted in fewer lambs being sold, leading to a lower net cash flow from the sheep flock under the afforestation interventions. However, there was a temporary increase in flock size during the period when native shrubs were available for browsing. This increase in flock size led to more lambs being sold, causing a short-term rise in the flock net cash flow. On average, the sheep flock cash flow for the base scenario was NZD 23,897 per year. The native shrubs intervention led to a 0.86% increase in the annual average sheep flock cash flow when planted at a 10% rate, but a 1.28% decrease when planted at a 20% rate. The reduction in sheep flock net cashflow under a 20% native shrub planting rate was primarily caused by drastic reduction in feed supply causing a large reduction in the flock size. The large reduction in flock size impacted on the stability of the flock structure, which in turn affected lambs sale and sheep flock net cash inflow post the browsing period.

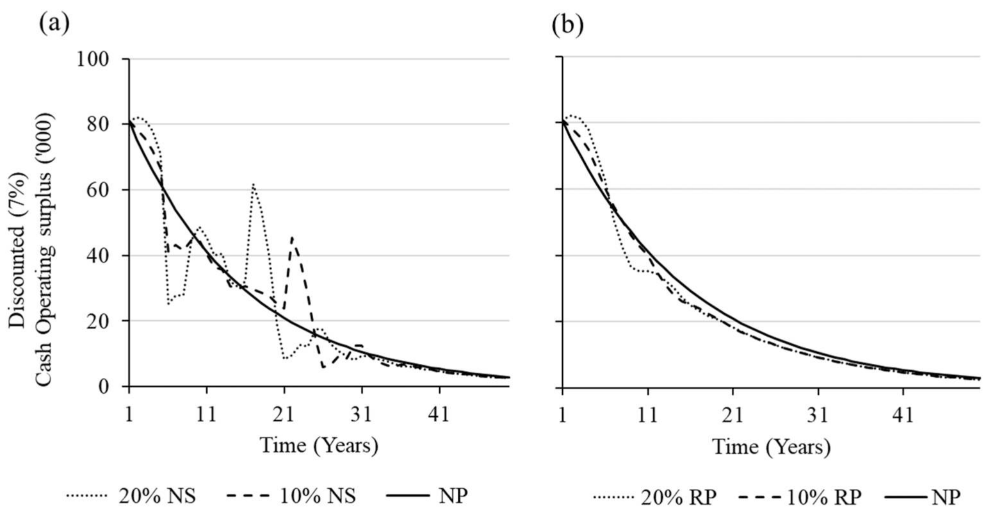

Figure 7. Sheep flock net cashflow at 7% discount rate for the base scenario and with (a) native shrubs (NS) or (b) radiata pine (RP) planted on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10% and 20%).

In contrast, the radiata pine intervention resulted in a 4.3% and 0.83% decrease in the annual average sheep flock cash flow at 10% and 20% planting rates, respectively. The larger reduction with radiata pine, particularly at the 20% planting rate, is likely due to the reduction in feed supply, as explained in the section 'Feed supply from the slope classes'.

Native shrubs and radiata pine cashflow

The discounted average annual cash flow over 50 years for radiata pine and native shrubs is shown in Table 3. The average cash inflow from radiata pine (from carbon trading and log sales) exceeded cash outflow by 105.9% at the 10% planting rate and 101.5% at the 20% planting rate. This indicates that planting radiata pine on the steep slopes can be profitable at current carbon and timber prices. Post planting expenses accounted for the largest share of cash outflow, making up 90.4% at the 10% planting rate and 91.2% at the 20% planting rate. Land preparation costs contributed 5.4% and 4.9%, and planting costs accounted for 4.2% and 3.9% at 10% and 20% planting rates, respectively. The high post planting expenses for radiata pine are due to tree management and harvesting operations.

In contrast, the cash outflow (expenses) exceeded the cash inflow (from carbon trading) for native shrubs, indicating that the native shrubs intervention was not a profitable intervention at the current carbon price (55.6 NZD/NZU). Planting costs (45.8% and 43.5% of total expenses) and post-planting expenses (47.7% for both planting rates) accounted for the largest proportion of cash outflow at the 10% and 20% planting rates, respectively. The cost of native shrub seedlings (NZD 2.65 per seedling) made up 80.6% of the establishment costs. This suggests that lowering the price of native shrub seedlings could significantly reduce planting expenses and improve net cash flow. Comparably, native shrub plant price was approximately eight times more than radiata pine seedlings (NZD 0.3/ seedling) (Lincoln University 2021).

The higher net cash flow for radiata pine compared to native shrubs can be attributed to its greater carbon stock accumulation approximately three times that of native shrubs (Ministry for Primary Industries 2017) as well as the additional income from log sales (Satchell 2018). Although native shrubs yield lower financial returns, they provide numerous non-financial benefits to society, the environment, the hill country landscape, and biodiversity, which were not factored into the model. Additionally, the model did not account for the costs of erosion control and environmental restoration after harvesting radiata pine. These costs can significantly reduce the net cash flow for radiata pine, especially when used on steep slopes (Satchell 2018; Kimberley et al. 2021).

Table 3. Annual average cashflow in terms of income (cash inflow), expenses (cash outflow) and net cashflow (cash operating surplus) over 50 years at 7% discount rate for native shrubs and radiata pine planted on an area equal to 10% of effective farm area (624 ha) at 20 and 10% planting rates.

	Native shrubs			Radiata pine			
Planting rate (%)	Carbon income	Total expenses	Net cashflow	Carbon income	Logs income	Total expenses	Net cashflow
10	3394	4489	−1095	9707	15,413	12,201	12,920
20	3963	5439	−1476	11,334	18,303	14,705	14,932

Sheep enterprise cash operating surplus (COS) with native shrubs on the steep slope

Figure 8 shows the trend in sheep enterprise COS over the simulation period when native shrubs are planted on steep slopes. With native shrub planting at both 10% and 20% rates, the COS remained lower than in the base scenario, except during years of higher lamb sales and carbon cash inflow, which produced sharp peaks in COS. This reduction in COS can be attributed to the initial establishment expenses for native shrubs, which were drawn from the sheep flock COS. The 20% planting rate incurred higher costs for land preparation and planting, leading to a more significant reduction in COS compared to both the 10% rate and the base scenario. On average, annual sheep enterprise COS with native shrubs was 3.7% lower at the 10% planting rate and 6.6% lower at the 20% rate, compared to the base scenario average (NZD 23,897). The greater reduction with a 20% planting rate can be attributed to reduced feed supply, which supported a lower flock size and therefore fewer lambs sold compared to native shrubs planted at 10% rate. Reducing the establishment costs of native shrubs can be supported through strategies such as scaling up native shrub nurseries, providing establishment grants and promoting natural revegetation. Carbon income from native shrubs can be enhanced through premium pricing, reflecting their co-benefits such as ecosystem restoration and long-term sustainability in agricultural landscapes. Additional opportunities can include introducing biodiversity credits, increasing carbon trade typical average years and integrating complementary enterprises such as honey production. Additionally, extending browsing periods could also support more sheep, potentially increasing lamb sales income.

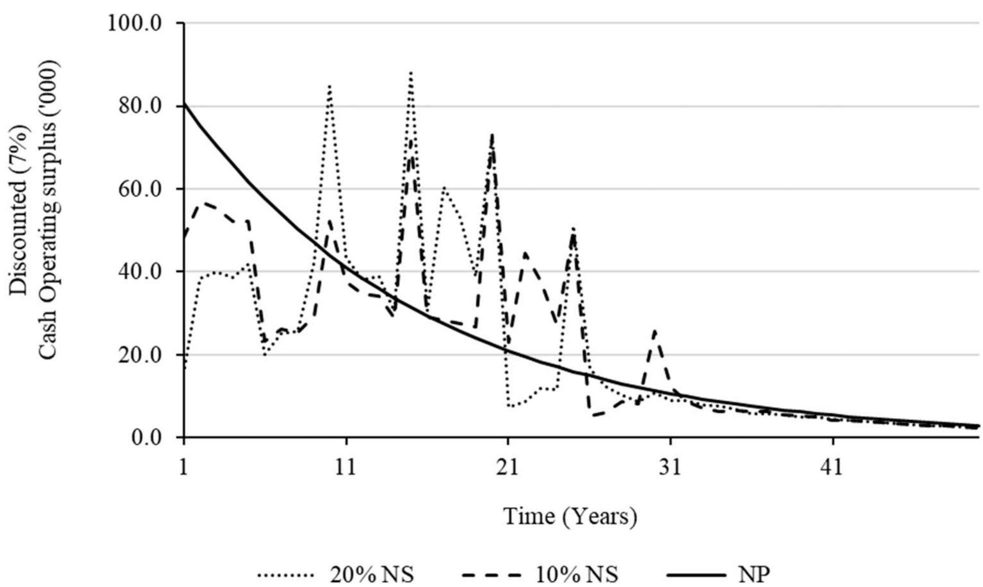

Figure 8. Sheep enterprise cash operating surplus (COS) at 7% discount rate with pasture (base scenario) and with native shrubs (NS) planted on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10% and 20%).

Sheep enterprise COS with radiata pine planted on the steep slope.

The cash operating surplus (COS) for the sheep enterprise with radiata pine was generally lower than for the base scenario throughout the simulation period, except during the years of carbon and log cash inflows (Figure 9). On average, the sheep enterprise COS with radiata pine was 49.8% higher at the 10% planting rate and 57.4% higher at the 20% rate compared to the base scenario (NZD 23,897). The greater COS with radiata pine can be attributed to the substantial carbon cash inflows and additional income from log sales, which resulted in a surplus COS after covering establishment expenses.

Net present value for using either native shrubs or radiata pine on the steep slope.

Table 4 displays the net present value (NPV) of the sheep enterprise under three discount rates (5%, 7%, and 10%) for the base scenario and with native shrubs or radiata pine planted at 10% and 20% rates on steep slopes. The NPV for the sheep enterprise with native shrubs at both planting rates was consistently lower than the base scenario across all discount rates, indicating that the cash flows from carbon trading and lamb sales could not offset the establishment costs of native shrubs at current prices. As expected, the NPV decreased with higher discount and planting rates; this is because future net cash flows lose value as the discount rate increases (The Treasury 2008). A 20% annual planting rate of native shrubs resulted in significantly lower net cash flow, further reducing the NPV. This suggests that, given the current cash flow from native shrubs, planting them at higher annual rates will lead to a greater reduction in the sheep enterprise's cost of production. Similar findings were noted for the sheep enterprise with native shrubs at a carbon price of 32 NZD/NZU (Wangui et al. 2021).

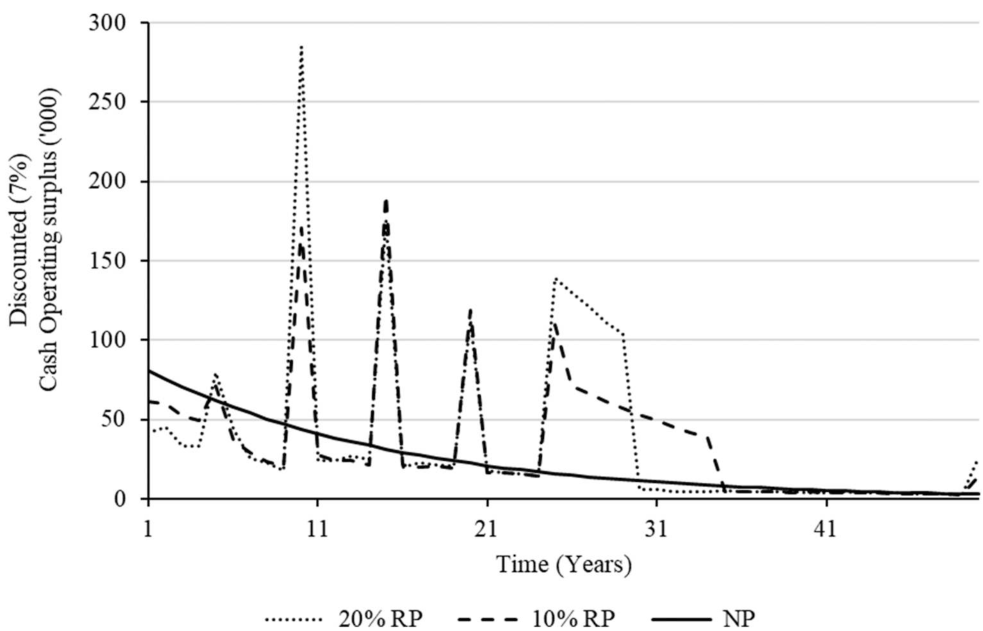

Figure 9. Sheep enterprise cash operating surplus (COS) at 7% discount rate with pasture and with radiata pine (RP) planted on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10% and 20%).

Table 4. Sheep enterprise net present value (NPV) at three discount rates (5%, 7% and 10%) with pasture and with native shrubs or radiata pine planted on an area equal to 10% of the effective farm area (624 ha) on the steep slopes at three planting rates (10% and 20%).

		Native shrubs		Radiata pine	
Discount rate	Pastures	10%	20%	10%	20%
5%	1,659,762	1,622,071	1,545,814	2,610,920	2,681,360
7%	1,278,418	1,199,486	1,129,872	1,840,535	1,898,707
10%	943,999	828,959	759,332	1,190,216	1,219,793

The NPV for the sheep enterprise with radiata pine was higher than that of the base scenario and the native shrubs intervention at both planting rates. This was due to increased cash inflows from logs revenue enhanced by income from carbon trading. In contrast to native shrubs, the NPV for radiata pine was greater at the 20% planting rate compared to the 10% rate across all three discount rates. The lower NPV for radiata pine at the 10% planting rate can be attributed to cash inflows (from carbon and timber) being spread over twice the number of years compared to the 20% planting rate. As a result, cash inflows occurring later in the spread period for the 10% planting rate had a greater reduction in value due to discounting, which explains the lower NPV. This suggests that radiata pine would be more profitable when planted at higher rates across all three discount rates.

Break-even carbon price for sheep enterprise with native shrubs

The modelled carbon price (55.6 NZD/NZU) resulted in higher NPV for the sheep enterprise with radiata pine and lower with native shrubs than the base scenario (Table 5). Therefore, the break-even carbon price was only estimated for the sheep enterprise with native shrubs. The estimated break-even price was higher across all discount and planting rates than in earlier estimates (Wangui et al. 2021). This increase was largely due to the current model's use of a generalised allometric function for native shrubs to estimate growth and carbon accumulation, while the previous model applied growth rates modulated using *Eucalyptus saligna* (Wangui et al. 2021). Although *E. saligna* grows faster than native shrubs, modulating its growth rate to approximate native shrub growth led to an underestimation of carbon accumulation for native shrubs. Carbon stock estimated in the current model was higher than those for Ministry for Primary Industries (2017) but was comparable to by Kimberley et al. (2014) for forestry native trees and shrubs in New Zealand. Higher carbon stock in the current model led to lower breakeven prices compared to the previous model. This is despite the current model using the averaging carbon-accounting method while the previous model used the stock-change carbon-accounting method (Wangui et al. 2021). Under the averaging

Table 5. Break even carbon price per New Zealand Unit (NZD/NZU) at three discount rates (5%, 7% and 10%) of using native shrubs on an area equal to 10% of the effective farm area (624 ha) on the steep slopes at two planting rates (10% and 20%)

	Discount rate (%)		
Planting rate (%)	5	7	10
10	64.2	81.5	118.5
20	78.7	97.3	137.4

method, carbon trading is limited once native shrubs reach an average age of 23 years (Kiro 2022), whereas the stock-change method allowed carbon trading over the entire 50 year simulation period (Wangui et al. 2021). The break-even carbon price relative to the modelled price increased with higher planting and discount rates, a trend driven by more negative net cash flow at the 20% planting rate and its amplification with increasing discount rates.

Limitations of the study and future improvements

This study aimed to provide insights into the impact of using native shrubs and radiata pine on feed supply and farm income when planted on a portion of steep slopes of hill country sheep and beef farm. Although the model aimed to replicate the farm characteristics typical of hill country sheep and beef farms, it did not fully account for the diversity of farming conditions. The following limitations and areas of improvement are acknowledged. The model assumed that farm conditions in hill country sheep and beef farms aligned to the modelled farm. However, hill country farms vary in agroecological conditions, soil properties and landscape characteristics which can influence native shrubs suitability, growth rate, carbon sequestration potential and fodder productivity. Additionally, changes in feed supply can impact on the beef herd dynamics which was assumed to be constant in the model. Future improvement to the model can integrate uncertainty analysis and scenario modelling to assess how the farms variability impacts on the outcomes. Sheep were assumed to prefer and consume native shrubs fodder based on wild herbivores foraging behaviours. However, fodder preference and herbivory vary among herbivores, potentially affecting the contribution of native shrubs to farm feed supply. Future studies on farmed ruminants native shrubs preference and intake can provide data to refine predictions of farm feed supply. The study used financial metrics to compare native shrubs with radiata pine. However, native shrubs provide non-financial benefits, such as biodiversity conservation, wildlife habitat, and landscape aesthetics, which enhance ecosystem services and farm sustainability. Future model improvements could estimate the financial value of these benefits while also incorporating an ecosystem services valuation framework to provide a more comprehensive comparison.

Conclusion

The inclusion of a radiata pine sub-model in the hill country sheep and beef farm model allowed for comparison of the impacts on the farming system of planting either native shrubs or radiata pine on the hill country steep slopes. Planting of either native shrubs or radiata pine led to a decrease in farm feed supply and was greater at 20% planting rate and with radiata pine. Reduction in farm feed supply was lower than the proportion of effective area removed from grazing indicating that afforesting the steep slopes has less effect on farm carrying capacity. Decrease in farm feed supply led to a reduction in sheep flock size and subsequently lambs sold. The reduction in lambs sold caused a decrease in the sheep flock net cashflow and the decrease was more at 20% planting rate and with planting of radiata pine. However, a comparison of the afforestation interventions to the base scenario showed that the radiata pine was profitable at the current carbon and log prices, while native shrubs had negative net cashflow at the current carbon prices. This suggests that, at current carbon prices, radiata pine may be financially more attractive to farmers than native shrubs. The carbon price required to make planting native shrubs break-even with the base scenario was 64.2 and 137.4 NZD/NZU for the best- and worst-case scenarios, respectively tested in this study. Policy interventions that lower the cost of establishing native shrubs and improve income potential to levels comparable with radiata pine could make native shrub a profitable and attractive option for hill country farmers. The limitations of this study include assuming that hill country sheep and beef farms align with the modelled farm, that sheep will prefer and consume native shrub fodder, and the exclusion of non-financial benefits of native shrubs. Future model improvements could include integrating uncertainty analysis and scenario modelling, updating feed supply estimates with farmed ruminants specific data on native shrub preference and intake, and incorporating an ecosystem services valuation framework to provide a more comprehensive comparison of native shrubs and radiata pine.

Author contributions

James C. Wangui: Conceptualisation, Methodology, Formal Analysis, Investigation, Data Curation, Visualisation, Writing – Original Draft, Writing – Review & Editing. **Sarah J. Pain and Peter R. Tozer**: Conceptualisation, Methodology, Software, Validation, Supervision, Resources, Investigation, Validation, Writing – Review & Editing. **James P. Millner and Paul R. Kenyon**: Conceptualisation, Methodology, Validation, Supervision, Funding Acquisition, Writing – Review & Editing, Project Administration.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

Data are available on request to the corresponding author.

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