Use of New Zealand Native Browse Shrubs on Sheep and Beef Hill Country Farms

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Abstract

Sheep and beef cattle farming on hill country through the historic clearing of native vegetation for pasture has caused biodiversity loss and increased the risk of soil erosion. Exotic tree species such as poplar and radiata pine can be used to control erosion, but there is current interest in using native plants on the hill country for indigenous biodiversity restoration in addition to erosion control. However, there is limited information on the forage value, biomass, carbon stock, and potential economic impacts of native plants compared to exotics species. This thesis was aimed to address the lack of information available on native shrubs and their comparison to exotics trees and shrubs. The forage feeding value results revealed that native shrubs had consistent nutritional composition across seasons, higher metabolizable energy, and lower crude protein than the exotic shrub *Salix schwerinii* (Kinuyanagi). Findings on *in vitro* fermentation characteristics showed that native shrubs were highly digestible, yielded higher volatile fatty acids, microbial proteins, and greenhouse gases than *S. schwerinii*. Estimation of biomass revealed that the native shrubs were similar in aboveground biomass accumulation, but differed in allocation to foliage, branch, and stem. *Melicytus ramiflorus* (Mahoe) had lower foliage biomass while *Coprosma robusta* (Karamū) had lower branch biomass, among the evaluated shrubs. Estimated carbon stock accumulation was higher for *Pittosporum crassifolium* (Karo) due to a greater woodier portion (branch and stem) than *M. ramiflorus* and *C. robusta* but lower than exotic trees. The data from the native shrub studies was used in the bioeconomic model and showed that planting native shrubs or radiata pine on steep slopes equal to 10% of the farm area would reduce farm feed supply. This reduction would result in a decrease in sheep flock size and sheep flock net cashflow, particularly with higher planting rates and with of radiata pine. While radiata pine had a surplus overall farm net cashflow, native shrubs had negative cashflow due to high seedling costs and low carbon income, making their use on the farm currently unprofitable at the modelled prices. The study's findings suggest that replacing exotic trees with native shrubs can provide high-quality summer browse for livestock. The decision to plant native shrubs on steep hill country slopes would depend on the farmer's financial situation and interest in biodiversity conservation and profits. However, reducing planting costs and increasing the carbon price would be necessary to make investing in native shrubs profitable and more attractive to farmers.

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List of Abbreviations

ABM	Aboveground Biomass
ADF	Acid Detergent Fibre
AIC	Akaike Information Criterion
AOAC	Association of Official Agricultural Chemists
BBM	Belowground Biomass
BD	Basal Diameter
CA	Canopy Area
CAI	Current Annual Increment
cBM	Component's Biomass
CD	Canopy Diameter
CH_4	Methane
CO_2	Carbon Dioxide
COS	Cash Operating Surplus
CP	Crude Protein
CT	Condensed Tannins
DBH	Diameter at Breast Height
DM	Dry Matter
GHG	Greenhouse Gas
ha	Hectare
HCM	Hill Country Sheep and Beef Farm Model
IRR	Internal Rate of Return
IVDMD	*In vitro* Dry Matter Digestibility
IVDOMD	*In vitro* Digestible Organic Content in Dry Matter
IVOMD	*In vitro* Organic Matter Digestibility
LUC	Land Use Capability
MAI	Mean Annual Increment
MAPE	Mean Absolute Percentage Error
MBM	Microbial Biomass
ME	Metabolizable Energy
MJ	Mega Joules
ML	Maximum Likelihood
MPI	New Zealand Ministry for Primary Industry
NDF	Neutral Detergent Fibre
NPV	Net Present Value
NSM	Native Shrubs Subsystem Model
NZ	New Zealand
NZ$	New Zealand Dollar
NZU	New Zealand Emission Unit
OLS	Ordinary Least Square
OMD	Organic Matter Digestibility
RCBD	Randomized Complete Block Design
RCD	Root Collar Diameter
RMSE	Root Mean Square Error
RPM	Radiata Pine Subsystem Model
SPH	Stems Per Hectare
SU	Stock Units
VFA	Volatile Fatty Acids

Chapter 1: General Introduction

1.1. Background of the Study

Agricultural expansion over the last 180 years in New Zealand has led to conversion of approximately 80% of the native vegetation to pasture and crop lands (Allen et al., 2013; Norton & Pannell, 2018; Pannell et al., 2021). The remaining 20% of the native vegetation are in nature conservation and unusable pockets in hill country sheep and beef farms (Allen, 2013; Norton, 2018; Pannell, 2021). The ecological consequences of clearing the native vegetation have been loss of biodiversity, increased pollution of waterways, rise in greenhouse gas emission and increased vulnerability to soil erosion (Blaschke et al., 2000; Basher, 2013; Fernandez, 2017). The negative ecological impacts are a threat to sustainable agricultural production, which is an important source of livelihoods, tradable products and income in New Zealand (Beef+Lamb NZ, 2020c).

Agricultural production is the major land user occupying over 50% of NZ landmass (Ministry for the Environment, 2010), of which approximately 63% is utilized for sheep and beef cattle farming (Beef+Lamb NZ, 2020c). The agricultural sector contributed approximately 59.4% of the total exports (Beef+Lamb NZ, 2020d) and approximately 4.2% to the national gross domestic product (GDP) in the year 2019 (StatsNZ, 2019b). More than 82% of the agricultural GDP was from livestock production, to which sheep and beef farming contributed approximately 37.2% (StatsNZ, 2019b). The sheep and beef sector is highly focused on the export market (Morris, 2013; Beef+Lamb NZ, 2020c) with approximately 94% and 83% of sheep and beef meat, respectively, exported and generating $7.2 billion in agricultural export revenues in the same year (Beef+Lamb NZ, 2020c). Although the number of sheep and beef cattle have declined by 15% and 7% to an estimated 27.4 and 3.2 million respectively over the decade ending in 2019, per animal production performance has greatly improved over the same period (Beef+Lamb NZ, 2020c, 2020b). Sheep and beef are complementary in pasture utilization and are commonly raised on the same hill country farms where pastures account for over 95% of their diet (Morris, 2013; Morris & Kenyon, 2014; Beef+Lamb NZ, 2020c).

Individual hill country sheep and beef farms can contain a mixture of flat (<12°), rolling (13° to 25°) and steep (>25°) slope classes (Lambert et al., 1983; Saggar et al., 2015), which on an average farm account for 11, 32 and 40% of the total effective farm area, respectively (Beef+Lamb NZ, 2020b). The slope classes range causes variability in soil and biophysical properties resulting in differences in land productivity and usability

(Lynn et al., 2009; Saggar, 2015; Kemp & Lopez, 2016). Flat and rolling slopes are mostly characterized by deep, well drained and relatively fertile soils suitable for cultivation of crops and pastures (Radcliffe et al., 1968; Lynn, 2009; Moot et al., 2009; Morris, 2014; Beef+Lamb NZ, 2020b). Steep slopes on the other hand can be relatively unproductive and prone to erosion for intensive agricultural use (Radcliffe, 1968; Lynn, 2009; Moot, 2009; Morris, 2014; Beef+Lamb NZ, 2020b). Thus, flat and rolling slopes are commonly sown with improved pastures and can support higher stocking densities, while steeper slopes are more suitable for grazing at lower stocking densities, plantation forestry and conservation of native biota (Lynn, 2009; Morris, 2013). The higher pasture production in the flat to rolling slopes can support between 7 to 13 stock units (SU) per hectare as compared to steep slopes that can only support less than 7 SU per hectare (Campbell et al., 1973; Blennerhasset, 2002). Although steep slopes can be used for grazing at low densities, stock tracks along the steep slopes are known to increase the likelihood of soil mass movement (Lynn, 2009; Ministry for the Environment & Stats NZ, 2019). It has been suggested that steep slopes greater than 35° are hazardous to grazing animals, unsuitable for mechanized agriculture and plantation forestry operations and can only be appropriate for conservation of native biota (Lynn, 2009). As such, there are concerns on the economic and environmental viability of continued use of the steep slope portions of land on hill country sheep and beef farms for grazing, considering the lower carrying capacity, susceptibility to erosion and the long term cumulative negative environmental impacts (Pollock, 1986).

Plantation forestry is an established option for the steep slopes utilization because of its economic potential in carbon trading and timber production while protecting the soil against erosion (Visser et al., 2018). Currently, plantation forests cover approximately 7% of New Zealand land mass with approximately 40% on the steep slopes, of which radiata pine (*Pinus radiata*) makes up more than 90% of the forestry tree species (Ministry for Primary Industries, 2014; Norton, 2018; Visser, 2018). Although plantation forestry can have economic benefits, its monoculture production limits biodiversity (Satchell, 2018). In addition, plantation forestry is a commodity enterprise and only becomes economically viable when trees are harvested (Maclaren, 1993; Hocking, 2003). Harvesting by clear-felling plantation forestry trees on the steep slopes exposes the soil to mass movement and greenhouse gasses emission and in addition results in loss of carbon sinks and carbon trading income (Satchell, 2018). In addition, log debris (slash) can be washed to low grounds and in water ways during storms causing destruction to the environment, properties and infrastructure (Satchell, 2018).

Alternatively, spaced poplar (Populus spp) and willow (Salix spp) have also been utilized for steep slopes and riparian erosion control, due to their ease of establishment, fast growth rate, ability for understory grazing and a potential source of supplementary fodder (Wilkinson, 1999; Kemp et al., 2001; McIvor et al., 2011). However, poplar and willow are non-native, deciduous, labor intensive and some hybrids are susceptible to some diseases and pest (McIvor et al., 2006).

Native vegetation is emerging as an alternative viable option for utilizing hill country steep slopes because of their adaptability, ease of natural regeneration and wide variety of species (Norton, 2018). Presently, native vegetation covers about 10 to 15% of New Zealand landmass (Allen, 2013; Norton, 2018), approximately 25% of which are on hill country sheep and beef farms where they occupy on average 13% of the farm area mainly on the unusable portions on the steep slopes (Norton, 2018). Although scantly explored, native vegetation can provide similar economic and environmental benefits like the exotic species such as erosion control, timber production, carbon sequestration and carbon trading income (Dodd & Ritchie, 2007; Bergin, 2014b). In addition, native vegetation are culturally valued and because of their taxonomic diversity they enhance biodiversity and landscape aesthetics (Dodd, 2007; Norton, 2018). Furthermore, some of the native vegetation are browsed by wild herbivores and could therefore be used as fodder source for the farmed ruminants (Forsyth et al., 2002, 2005). However, there is scant information on their suitability, management and the economic impacts when integrated into the farming system (Norton, 2018). Therefore, the aim of this study was to evaluate the potential use of selected browsable native shrubs on steep slopes of hill country sheep and beef farms in New Zealand. The browsable native shrub species studied included *Hoheria populnea* (Houhere), *Pittosporum crassifolium* (Karo), *Griselinia littoralis* (Pāpāuma), *Coprosma robusta* (Karamū), *Melicytus ramiflorus* (Māhoe) and *Pseudopanax arboreus* (Whauwhaupaku). An exotic osier willow was included as control species because it is commonly utilized for erosion control and supplementary fodder on New Zealand hill country sheep and beef farms.

1.1.1. Specific objectives

The aim of the study was addressed using the following specific objectives, to:

1. Assess the impact on farm feed supply, flock size, and economics of planting native shrubs on the steep slope portion of hill country sheep and beef farms,
2. Evaluate the nutritional composition of browsable native shrubs,
3. Determine the *in vitro* fermentation kinetics, fermentation products (volatile fatty acids, microbial protein, and greenhouse gases) and digestibility of browsable native shrubs,
4. Estimate the components (stem, branch, and foliage) and aboveground biomass and developing allometric functions to predict biomass variables and carbon stock of native shrubs, and
5. Compare the impact on farm feed supply, flock size and economics of planting either native shrubs or radiata pine on the steep slope portion of hill country sheep and beef farms.

1.1.2. Study structure

A literature review was conducted to identify knowledge gaps regarding the use and role of native shrubs in hill country sheep and beef farms on steep slopes (Chapter 2). The identified gaps were then used to structure the rationale and formulate specific objectives of this study (Chapter 1). Each objective was addressed in a separate research chapter. Chapter 3 describes the use of a bioeconomic simulation model to assess the impact of using native shrubs on the steep slopes of an average hill country sheep and beef farm, including the effects on feed supply, flock size, and economic outcomes. The simulation model used in Chapter 3 relied on limited literature data on native shrubs, which highlighted the need for further research. Chapters 4 and 5 addressed some of these gaps by evaluating the nutritional composition and fermentation properties of native shrubs, respectively. In Chapter 6, the biomass and carbon stock of browsable native shrubs were determined, and predictive allometric functions were developed. The native shrub species studied in Chapters 4, 5, and 6 varied because of seasonal and location availability of the native shrubs samples. In Chapter 7, the new information on native shrubs was incorporated into an updated bioeconomic model, which included a sub-model for radiata pine. The improved model was used to re-assess the impact of using native shrubs versus radiata pine on hill country sheep and beef farms. Finally, Chapter 8 provided a general discussion of the findings, study limitations, future research directions, implications, and conclusions.

Chapters 4, 5, and 6, which focused on experimental research, followed the classic manuscript format with separate results and discussion sections. However, Chapters 3 and 7, which deal with simulation modeling, presents the results and discussion sections together. This approach was adopted to minimize redundancies and improve coherence in the presentation of the research.

Chapter 2: Literature Review

2.1. History of Sheep Farming in New Zealand

Sheep farming in New Zealand started approximately 180 years ago and has evolved to meet the changing market demands, ecological conditions and varying topography (Campbell, 1973; Moot, 2009). Merino sheep mainly imported from Australia were the initial breed farmed for their fine wool targeted for the export market (Campbell, 1973). Population increase in the 1860s led to increased local demand for meat which encouraged importation of British meat breeds such as Romney Marsh, Leicester, Lincoln and Cotswold that were crossed with Merino to increase meat production (Campbell, 1973). The demand for the meat breeds was further heightened by the opening of the frozen-meat market in England in the 1880s (Tom, 2016; Sutherland, 2018). This saw a robust growth and expansion of sheep farming throughout New Zealand which caused widespread farming landscape change and development of breeds suited to the evolving farming environment. Native vegetation was extensively cleared and exotic grass and legume species introduced to increase land productivity for grazing (Swaffield & Hughey, 2001; McIntyre, 2007). By the 1920s the Romney Marsh breed constituted more than 70% of the sheep farmed in New Zealand (Campbell, 1973). Despite the high preference, Romney breed had low fecundity prompting the development of Coopworth breed in the 1950s by crossing Romney with Border Leicester to increase the flock lambing percentage (Campbell, 1973). Further, expansion into the steep country demanded an agile breed which informed cross-breeding of Romney and Cheviot to produce the Perendale breed (Campbell, 1973).

As public mindfulness on health and diet became widespread in the 1990s, the use of terminal breeds such as Poll Dorset and Suffolk became popular to produce larger and leaner breeds preferred by the market, compared to the Southdown which produced a smaller fatter carcass (Campbell, 1973). More recent breeding decision changes prompted the use of crossbreeding, much of which included the use of Finnish Landrace, East Friesian and Texel breeds to produce composite breeds with high fecundity, milk yield and growth rates to maximize farm productivity and profitability (Brito et al., 2017). There are currently more than 100 sheep breeds and composite types for terminal mating, dual-purpose, wool, meat, and dairy production, with the Romney breed being the most common (Moot, 2009; Dodds et al., 2013).

Over the past century, the sheep population in New Zealand has increased from approximately one million in 1880s to a peak of more than 70 million in the early 1980s before declining to approximately 26 million presently (Beef+lamb NZ, 2021) (Figure 1). The decline has resulted predominantly from agricultural diversification, driven by other farming systems (e.g. dairy cattle and deer farming) being more profitable on a given class of land, retirement of land, and improved reproductive efficiency of the breeding ewes (Morris & Kenyon, 2014; Tom, 2016). However, sheep farming still dominates the New Zealand agricultural landscape, accounting for more than 71% of farmed ruminants (Beef+lamb New Zealand, 2017) and together with beef occupy approximately 40% of the farmed land (Norton, 2018). Sheep production in New Zealand is exclusively based on temperate grasslands with more than 85% of the sheep diet obtained from grazing on perennial pastures (White et al., 2010; Robinson et al., 2011).

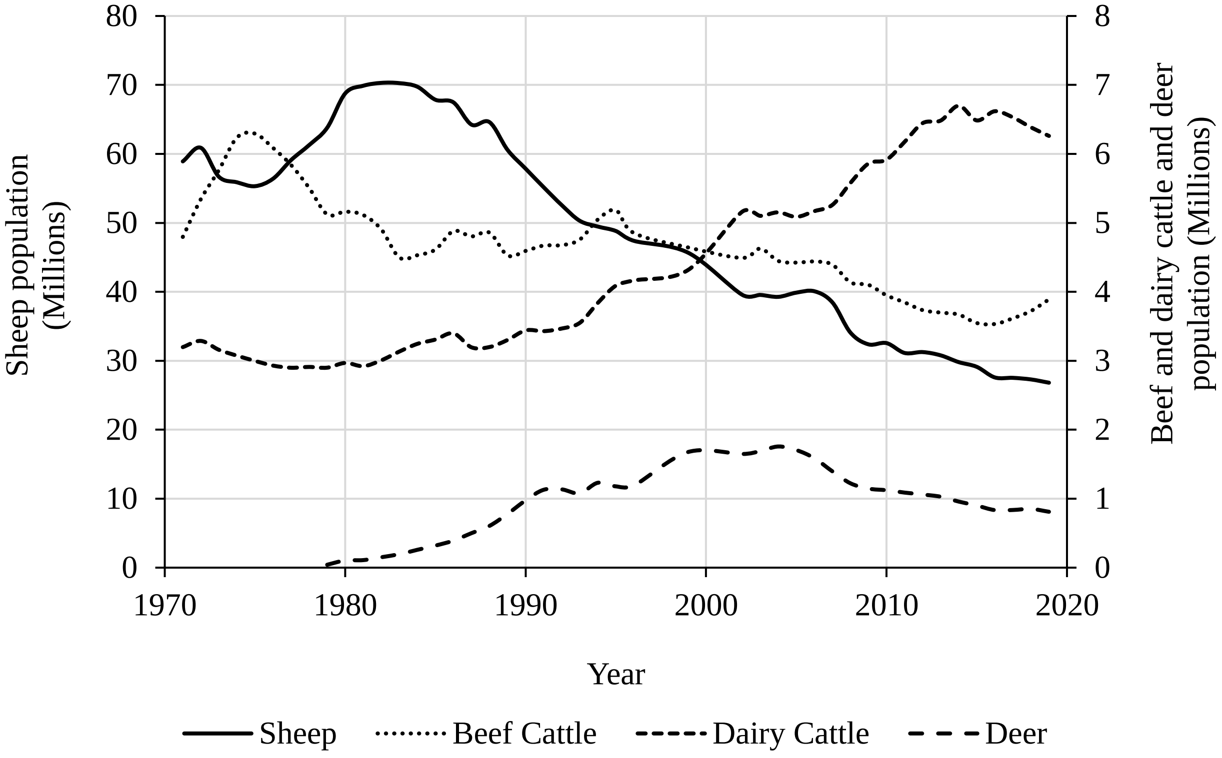

Figure 1. Trends in sheep, beef cattle, dairy cattle, and deer population from the year 1971 to 2019 (Data source: https://www.stats.govt.New Zealand/indicators/livestock-numbers)

2.2. Classification of Sheep Farming Systems in New Zealand

It’s insuperable to use a single approach to classify global livestock production systems due to the diversity of genetic resources, farming environments and production objectives (Robinson, 2011). Hence, most classification systems are regional and focus on the dominant farming activity (i.e., crops or livestock) to characterize, group and map similar farming systems (Hans, 1971; Seré & Steinfeld, 1996; Dixon et al., 2001; Robinson, 2011). Essentially, classification of livestock production systems should be hierarchical, consistent, flexible and easy to map (Robinson, 2011).

The New Zealand geographical position and varied topography resulting in a myriad of biophysical environments and land uses (White, 2010). This diversity makes characterization of the farming systems multifaceted. Thus, features such as geographic properties, climate, land use capability and farming activities are used to describe New Zealand sheep and beef cattle production systems (Beef+lamb New Zealand, 2017; Cranston et al., 2017; Morris & Kenyon, 2014; Statistics New Zealand, 2008; Stringleman & Peden, 2020). Topography and elevation have been used to classify New Zealand grasslands broadly into high, hill and flat or rolling country (Morris, 2013). The grasslands differ in pasture productivity (Table 1), increasing from the high to flat or rolling country (Morris, 2013). Pasture productivity is determined using carrying capacity and is expressed in stock units (SU). Therefore, flat or rolling topography has highest and high country grasslands the lowest (Morris, 2013). High country grasslands are found in the mountainous areas with altitudes above 700 meters and are characterized by variable and limiting climatic conditions (Swaffield, 2001; Kemp, 2016). Hill country occupies the lowlands, hills and steep-lands at altitudes above 300 meters and with slopes greater than 15°, while the flat and rolling country occur at altitudes below 350 m in the fertile alluvial lowlands (Swaffield, 2001; Kemp, 2016).

Table 1. Typical New Zealand hill and high country topography and their respective area, pasture production, livestock numbers (Millions) and carrying capacity in stock units per hectare (SU/ha).

Topography	Area (Million ha)	Pasture DM (t/ha) *	Sheep	Beef	Dairy	SU/ha
High Country	4.5	2.0	2.5	0.1	0	0.7
Hill Country	5.0	7.0	20.3	1.9	0.2	7.5
Flat to Rolling country	4.5	11.0	26.7	2.9	14	14

Source: (Morris, 2013). *DM is Dry Matter, t is tonnes.

A farming system classification describing land capabilities and potential to support vegetation and livestock have been reviewed by Lynn (2009). The land use capability (LUC) classification considers climate, topography, soil properties and vegetation cover to describe eight classes (Table 2) that decrease in agricultural potential in ascending order (Lynn, 2009). Broadly, LUC 1 to 4 are high potential lands for arable farming, while LUC 5 to 8 are non-arable and account for about 72% of land in New

Zealand (Lynn, 2009). LUC 1 is found on flat topography (0°- 7° slope) with minimal physical limitation and support multiple land uses, LUC 2 has similar slope and land uses, but with slight physical limitation from erosion. LUC 3 has an undulating terrain (4°- 15° slope) and moderate erosion, stoniness and waterlogging limitations and can be used selectively for multiple land uses, while LUC 4 occurs on strongly undulating (16°- 20° slope) areas and has severe physical limitations for arable farming, only supporting occasional crop farming in addition to pasture production. The LUC 5 has moderate steep (21°- 25°) and is unsuitable for arable farming but with trivial limitations to pastoral production, viticulture, and agroforestry. LUC 6 has slopes >26° with erosion as the main limitation to pasture growth and only suitable for grazing and agroforestry. LUC 7 has slopes >35° and severe physical limitations to perennial vegetation and only suitable for controlled grazing, while LUC 8 is found on extremely steep lands with severe physical limitation for agricultural use. According to LUC classification, sheep farming can be carried out in all except LUC 8 due to the extreme physical restriction (Lynn, 2009). Although largely influenced by altitude, it is common to have several LUC on a single farming unit (Burggraaf et al., 2018).

Table 2. Land Use Capability classes and their respective area in the North and South Islands in New Zealand

LUC Class	Area ('000 ha)			% Total	Land Use
	North Island	South Island	Total		
1	1525	345	1870	0.7	Arable farming, pastoral grazing and agroforestry
2	6958	5062	12020	4.5	
3	10645	13778	24423	9.2	
4	13004	14769	27773	10.5	
5	935	1167	2102	0.8	Non-Arable, pastoral grazing and agroforestry
6	40787	33943	74730	28.1	
7	27746	29148	56894	21.4	
8	10154	47853	58007	21.8	Non-agricultural
Water bodies	1643	4779	6422	2.4	Conservation
Residential	1149	316	1465	0.6	Built up areas
Total	114546	151160	265706	100	

Source: (Lynn, 2009)

An alternative classification system that combines geographic properties, farming systems and LUC to classify New Zealand sheep production systems into eight farm types (Table 3Table 3) has been outlined by Beef+lamb New Zealand (2017) and Cranston et al. (2017). The farm types are described using their geographic location, topography and elevation and characterized by their dominant LUC and farming system (Moot, 2009). Geographic location delineates the North and South Islands, while topography and elevation describe the location of the farm within the landscape (Campbell, 1973). Subsequently, LUC defines the land properties and use capabilities, while farming system specify the production objectives for the farm (Lynn, 2009). The eight farm types are described briefly in the following subsections.

Table 3. Sheep production farm types, land use and respective sheep population in New Zealand for the year 2019 to 2020

Class	Farm type	Farms	Area (ha)	Stock Units	Average SU/ha	Sheep ('000)
1	South Island high country	200	7929	10113	1.3	8585
2	South Island hill country	620	1496	6639	4.4	4410
3	North Island hard hill country	920	798	6310	7.9	4057
4	North Island hill country	3055	429	4068	9.5	2448
5	North Island Intensive finishing farms	1045	290	2865	9.9	1522
6	South Island finishing- breeding farms	1820	394	3727	9.5	2199
7	South Island Intensive finishing farms	1040	230	2647	11.5	2564
8	South Island mixed cropping and finishing farms	465	427	3547	8.3	1823
Total		9165	11993	39916		27608

Source: (Campbell, 1973) and https://beeflambNew Zealand.com/data-tools/farm-classes

2.2.1. *Class 1: South Island high country*

These farms are found in the high-altitude mountainous area between the South Alps snowline and low altitude valleys and are characterized by very cold winters and hot summers (Swaffield, 2001). The climatic conditions, terrain and soil type support indigenous tussock grassland and are mainly for pastoral merino farming (Campbell, 1973; Swaffield, 2001). Pasture production varies with the topography and pasture improvement, with unimproved pastures yielding 0.3 to 1.0 DM (t/ha), improved pastures in steep areas 2.0 to 5.5 DM (t/ha) and in flat areas 4.0 to 10 DM (t/ha) (Moot, 2009). Due to the harsh conditions and a short growing season, only about 20% of the area has improved pastures which supply over 80% of the feed needs (Moot, 2009). The farms have a low carrying capacity of an average of 0.7 SU per ha typical of LUC 6 to 7 (Ian et al., 2009).

2.2.2. *Class 2: South Island hill country*

These grasslands are located on the lowlands, hills and steep-lands and generally have a slope greater than 15° (Kemp, 2016). They are characterized by shallow soils, stoniness, low soil pH and variable rainfall distribution resulting in unreliable pasture production with yields of about 1.0 to 6.0 DM t/ha, typical of LUC 4 to 5 (Lynn, 2009; Moot, 2009). Dual-purpose sheep together with beef cattle under extensive production dominate the farming landscape with an estimated carrying capacity of about 2 to 7 SU per ha of which, about 75% of the wintered stock units are sheep (Campbell, 1973).

2.2.3. Class 3: North Island hard hill country

These farms are located on the steep hills prone to erosion and low soil fertility and support pasture yields of about 2.0 to 6.0 DM t/ha, which are characteristics of LUC 5 to 7 (Lynn, 2009; Moot, 2009). However, climatic conditions are favorable for year-round pasture production if soil fertility is improved and woody weeds encroachment controlled (Moot, 2009). The farms are suitable for the extensive production of dual-purpose sheep together with beef cattle at carrying capacity of 6 to 10 SU per ha (Campbell, 1973). Most of the stock units are finished for slaughter and a significant proportion sold in-store condition (Hawkins & Wu, 2011).

2.2.4. Class 4: North Island hill country

These farms are characterised by varying proportions of steep, flat and rolling country and have higher soil fertility than hard hill country (Fraser et al., 2016) and characteristic to LUC 4 to 5 (Lynn, 2009). The farms utilise improved pastures in their cultivatable areas and have an estimated annual yield of 5.0 to 8.0 DM t/ha and carrying capacity is about 7 to 13 SU per ha (Campbell, 1973; Moot, 2009). Mixed sheep and beef cattle farming is the dominant enterprise with sheep accounting for approximately 56% of SU (Campbell, 1973; Fraser, 2016). Lamb in prime condition for slaughter or in forward store condition are the major farm outputs (Campbell, 1973).

2.2.5. Class 5: North Island intensive finishing farms

These farms are on the flat rolling easy country with properties of LUC 2 to 3 and generally characterised by deep fertile soils that support high pasture production of about 10 to 15 DM t/ha annually (Lynn, 2009; Moot, 2009). The farms use improved pastures of perennial ryegrass mixed with white clover and have an estimated carrying capacity of 8 to 15 SU per ha (Campbell, 1973; Moot, 2009). Store lambs and replacement ewes are commonly sourced from the surrounding hill and hard country and lambs are finished and sold for slaughter in prime condition (Campbell, 1973).

2.2.6. Class 6: South Island finishing-breeding farm.

These are the dominant farm types in the South Island and are found in the lowlands flat or undulating plains with very fertile soils and variable rainfall distribution typical to LUC 2 to 3 (Lynn, 2009; Moot, 2009). The farms are used for mixed livestock farming and arable crop farming with a carrying capacity of about 6 to 11 SU per ha (Campbell, 1973). Sheep farming is the main farm enterprise used for breeding and lamb finishing under extensive production system (Campbell, 1973; Moot, 2009). Improved pastures of perennial rye grass and white clover are the main sources of feed with annual yields of 7.0 to 10.0 DM t/ha with a potential of more 5 DM t/ha under irrigation, especially in the drier areas (Moot, 2009). Most farms plant supplemental forages such as lucerne and brassica in approximately 40% of their land and use it for priority feeding and during pasture shortages (Moot, 2009).

2.2.7. Class 7: South Island intensive finishing farms

These farms are found in the summer safe areas in the lower hills that are generally gently rolling, have very fertile soils and slight limitation to erosion that is a characteristic of LUC 2 to 3 (Lynn, 2009). They are considered high producing grasslands and are used for mixed livestock and some cash crop cultivation with sheep enterprise as the main source income (Campbell, 1973; Moot, 2009). The farms have a carrying capacity of 10 to 14 SU per ha and are used for intensive finishing of lambs for slaughter in prime condition (Campbell, 1973). Pastures utilized include the Nil endotypes and hybrid ryegrass, timothy grass, white and red clovers and chicory with an annual yield of 10 to 15 DM t/ha that are supplemented with bulb brassica to provide additional 15 to 20 DM t/ha during winter (Moot, 2009).

2.2.8. Class 8: South Island mixed cropping and finishing farms.

These farms are found in the fertile alluvial plains with deep soils and minimal physical limitations characteristic of LUC 1 to 2 and are suitable for mixed crop and livestock farming (Lynn, 2009). Due to their high versatility, cereal crops form the main economic activity and sheep finishing as a complement enterprise (Campbell, 1973; Moot, 2009).

2.3. Sheep Management in New Zealand

Sheep management practices follows the annual seasonal sequence, but there are farm type disparities due to differences in breeds utilized and farming environment (Campbell, 1973). The New Zealand climate is intricate, ranging from temperate alpine in the mountainous areas to warm sub-tropical in Northland (Macara, 2018). Nonetheless, the climate patterns can be separated into four overlapping seasons; spring (September to November), summer (December to February), autumn (March to May) and winter (June to August) that differ in weather elements; ambient temperatures, precipitation and solar radiation (Macara, 2018). Ambient temperatures are highest during summer, gradually decrease through autumn and lowest in winter before rising through spring to peak in summer (Figure 2(a)). Total seasonal rainfall is near uniform but highest in winter and lowest in summer with the western regions experiencing higher rainfall than the eastern parts (Figure 2(b)). Like the ambient temperature trend, solar radiation expressed as total sunshine hours is highest in summer and lowest in winter and gradually decreases through autumn and increases through spring.

Weather elements shape plants and animals’ adaptive mechanisms by influencing their responses to seasonal changes. The notable adaptive response in temperate pastures is adjustment of growth and development (Figure 3) with changes in weather. In long day species, growth rate is highest in the vegetative, steady in the reproductive and lowest in the dormant phase (Demanet et al., 2015). The vegetative phase corresponds to spring, reproductive to summer and the dormant phase to winter (Demanet, 2015; Burggraaf, 2018).

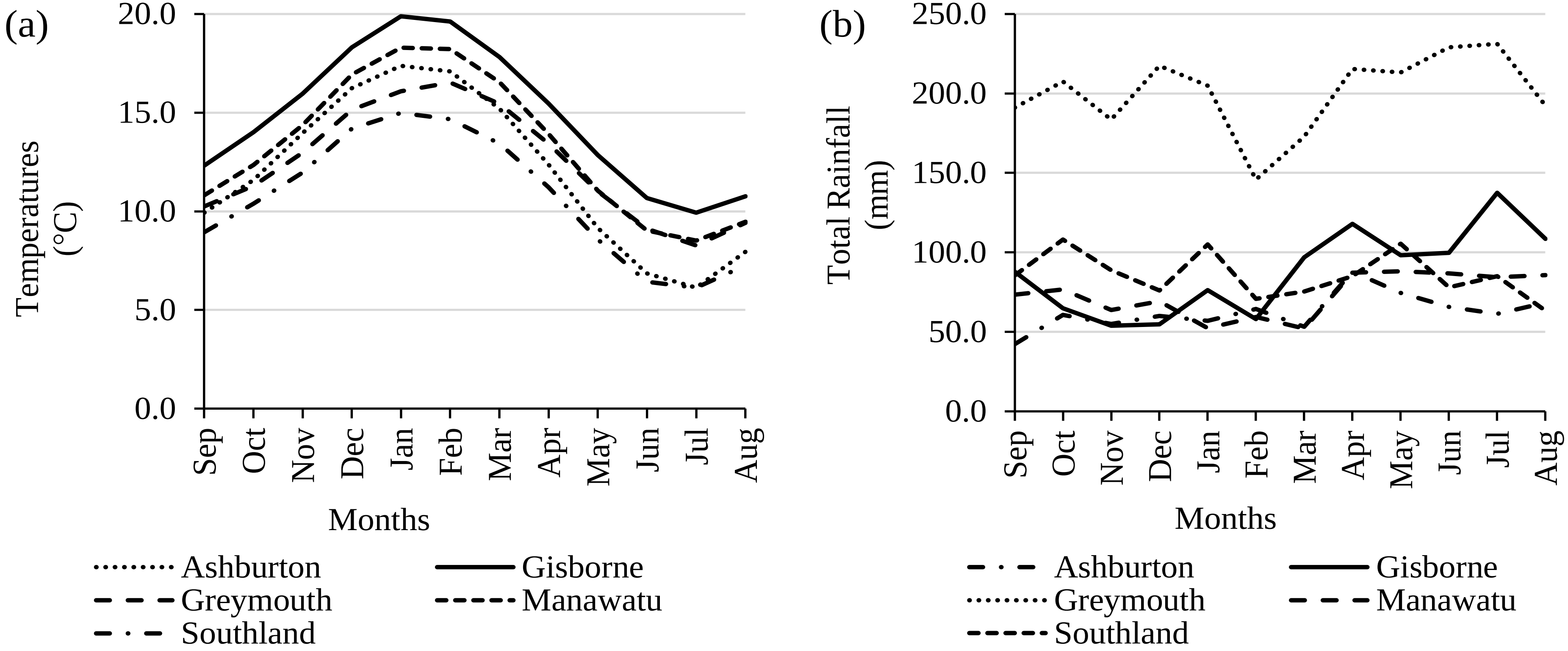

Figure 2. Monthly mean temperature (a) and total monthly rainfall (b) for five sheep farming districts in New Zealand for the years 2008 to 2019 (Data source: https://www.cliflo.niwa.co.nz/)

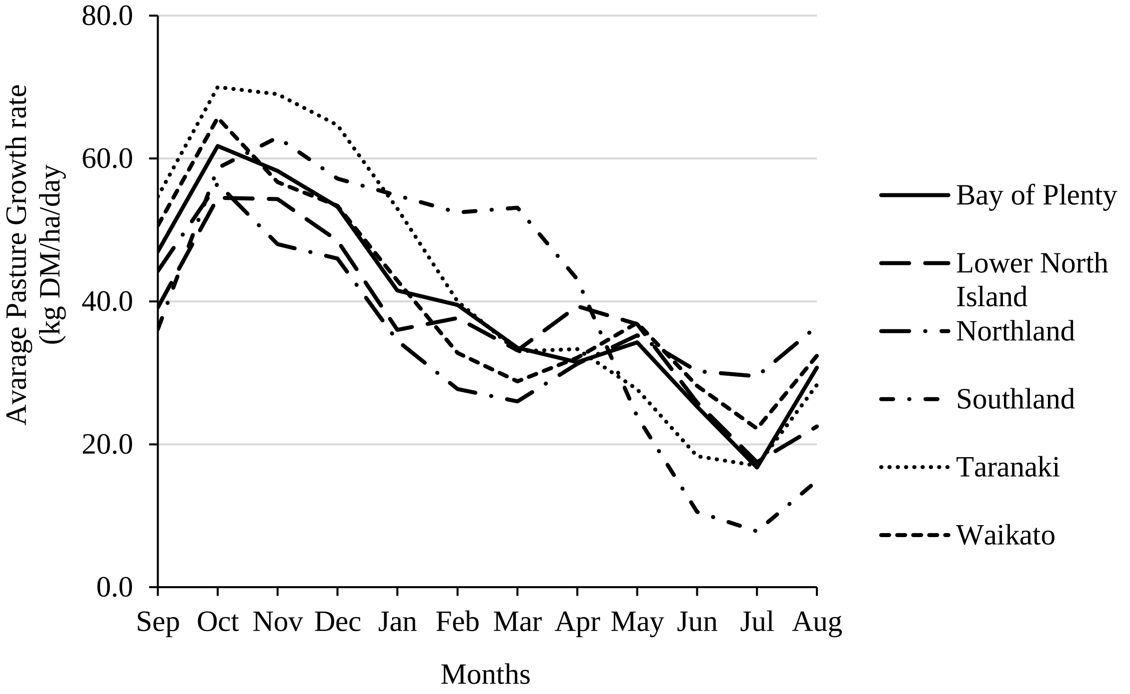

Figure 3. Average rye/clover pasture daily growth rate (Data source: www.dairyNZ.co.New Zealand/feed/pasture-management/pasture-growth-data/)

The seasonal weather change causes variability in pasture quantity and quality, which predisposes temperate animals to periodic thermal and nutrition stress respectively (Demanet, 2015). As an adaptive mechanism, temperate animals show behavioral, metabolic and physiological responses that suit prevalent environmental conditions (Robinson, 2011). Hence, sheep management practices are aligned to the seasonal sequences with an objective of minimizing environmental stresses and maximizing flock productivity (Campbell, 1973). Seasonal environmental stresses of economic importance in New Zealand sheep farming include feed and water quality and quantity variability, thermal stress and diseases, pests, and parasites prevalence.

2.4. Seasonal pasture production and management in New Zealand

2.4.1. Spring Season

This season is characterized by an increase in ambient temperature and solar radiation and a decrease in precipitation experienced in the winter season (Macara, 2018). The changing weather accelerates pasture growth and accumulation of dry matter (Tuck et al., 2013) and corresponds with a period of high feed demand from the lactating ewes (Beef+Lamb NZ, 2012). Pasture management during this season aims at maximizing utilization while at the same time avoiding overgrazing (Tuck, 2013). This is achieved through monitored rotational grazing or set stocking to maintain pasture heights of above 1 cm or below 10 cm, unless being conserved for hay or silage (Beef+Lamb NZ, 2012). Spring pastures lower than 1 cm are prone to weed invasion and soil erosion that lowers pasture quantity and quality available in the succeeding seasons and lowers the longevity of the sward (Beef+Lamb NZ, 2012; Tuck, 2013).

2.4.2. Summer Season

This is the hottest and driest season in New Zealand, characterized by above-average temperatures and intermittent rains and often result in drought in the dry areas (Macara, 2018). The ambient conditions progressively cause a decrease in pasture and water quality and quantity (Burggraaf, 2018), heightened risk of heat stress and proliferation of pest and parasites (Beef+lamb NZ, 2018). The effects of ambient condition on pastures quality and quantity differ with pasture mix and geographic location and is more pronounced in the dry and hot areas (Burggraaf, 2018). Hence, summer pastures management aims at maximizing utilization and minimizing accumulation of stems and dead matter by the erect species that suppress the prostate species (Burggraaf, 2018).

2.4.3. Autumn Season

This season succeeds summer and is characterized by gradual decrease in ambient temperatures and day-length and an increase in rainfall (Macara, 2018). The changes in ambient condition results in a gradual shift in physiological responses in temperate plants and animals. Long-day pastures gradually decrease growth rate and yield but increase in lushness (Moot, 2009), while sheep get into the breeding season (Campbell, 1973). Pasture management during this season is targeted to maximize pasture cover and minimize deficit during the upcoming winter season, when the demand by the pregnant ewe is high.

2.4.4. Winter Season

This is the coldest season characterized by heavy rainfall in most parts of New Zealand and snow fall in the mountainous and high-altitude areas (Macara, 2018). Due to low yield of long-day pastures, day-neutral forages such as turnips, brassica, kales are used to supplement dietary needs in mid to late gestation in some farms, while others utilize hay or silage conserved during spring and summer (Moot, 2009).

2.5. Challenges in Hill Country Sheep and Beef Farms

New Zealand hill country can be ecologically fragile due to its sloping nature (Section 2.2) that predisposes it to environmental limitations and associated problems. The limitations can be broadly grouped into physical and biological challenges. The major physical challenges in hill country can include soil erosion, high soil drainage, steep rugged terrain and climate variability while biological problems are weeds and pest invasion (Smith et al., 2007). The following section will focus on soil erosion as it is directly related to this study.

2.5.1. Soil erosion

Soil erosion is the main threat to hill country environment and farming economies (Blaschke, 2000; Fernandez, 2017). The erosion of the fertile soil leads to reduced soil fertility and productivity, consequently affecting farm income and profitability (Ministry for the Environment & Stats NZ, 2019). Damage from severe erosion increases farm costs in terms of properties repair and replacement and erosion control measures (Basher, 2013; Fernandez, 2017). The loss of the soil into water ways causes sedimentation and pollution which lowers the water quality and negatively affects aquatic systems (Blaschke, 2000; Ministry for the Environment & Stats NZ, 2019). Further, soil erosion lowers the land carbon sequestration which accelerates climate change and variability and its effects (Basher et al., 2018; Ministry for the Environment & Stats NZ, 2019).

There is variation in the causes, form and extent of erosion between the New Zealand North and South Islands due to their differences in geology, anthropogenic influence and climatic characteristics (Cumberland, 1944; Basher, 2013). Different from the South Island where erosion is mainly due to natural forces, anthropogenic activities are the main cause of severe and extensive erosion in North Island hill country (Cumberland, 1944; Basher, 2013; Fernandez, 2017). The conversion of native forest and shrubland into extensive pasturelands over the last millennia is attributed to accelerated and more expansive erosion in hill country (Blaschke, 2000; Basher, 2013; Fernandez, 2017). Trees and shrubs roots are deep and more extensive and can stabilise steep slopes by forming root networks that hold the soil and thus their removal can cause soil instability on steep slopes triggering massive erosion (Marden et al., 1992; Basher, 2013). It is estimated that more than 192 million tonnes of soil is eroded annually in New Zealand, of which, approximately 60% is from the North Island and more than 44% is displaced from pastoral farms (Basher, 2013; Ministry for the Environment & Stats NZ, 2019). The most widespread types of erosion in hill country are mass movement, gully and streambank erosion with mass movement the most dominant (Basher, 2013; Fernandez, 2017).

Mass movement includes deep and shallow (landslips) landslides, slumps and earthflows (Basher, 2013) and can occur on unstable slopes with elevation as low as 15° particularly in areas with tertiary soft rocks such as found in inland Whanganui, Hawkes bay and East Coast (Basher, 2013; Ministry for the Environment & Stats NZ, 2019). Landslips are the most common mass movement erosion and approximately 60% of New Zealand hill country land is highly vulnerable (Crozier, 2005) with the largest proportion of land at risk located in Manawatu-Wanganui and Gisborne regions (Ministry for the Environment & Stats NZ, 2019) (Figure 4).

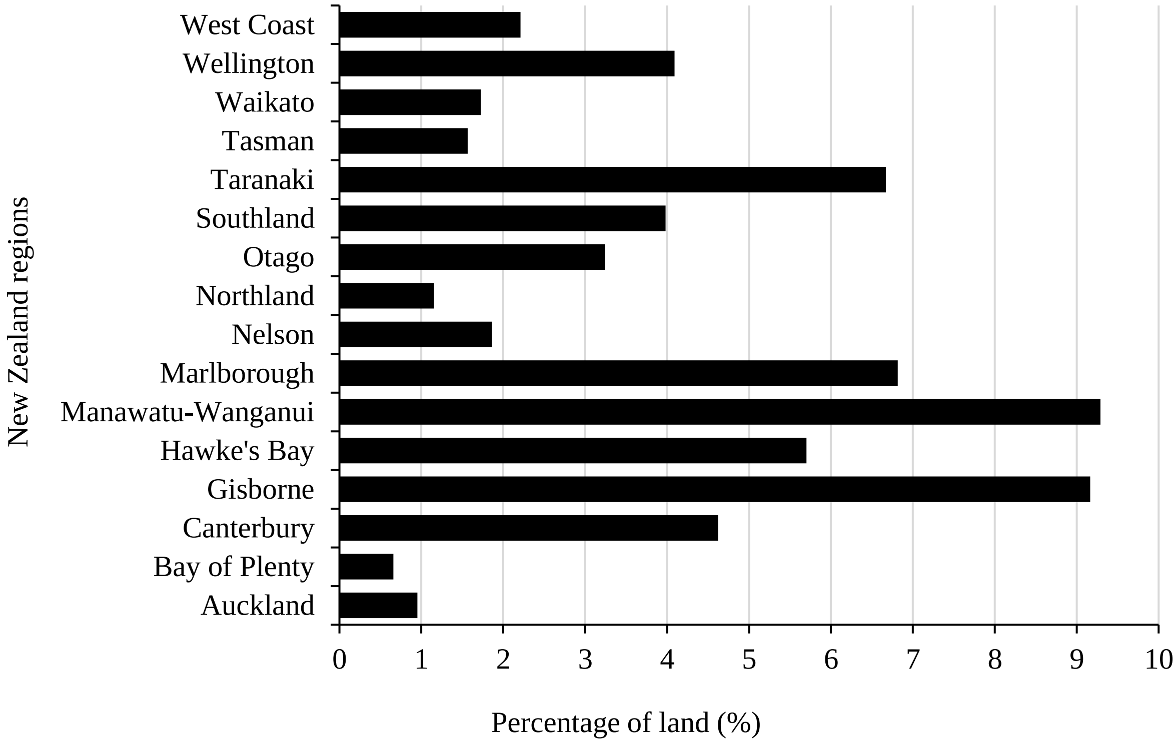

Figure 4. The percentage of land at high risk of landslide erosion by regions in New Zealand (Data source: https://statisticsnz.shinyapps.io/).

Landslips are naturally triggered by heavy rainfall and seismic activity with human actions such as land use changes, deforestation and mining increasing land susceptibility by destabilizing slopes (Brown, 1983; Crozier, 2005; Glade, 2003; Korup, 2005; Luckman et al., 1999; Rosser et al., 2017). Landslips can cause sudden loss of pasture, expose the land to erosive agents and on a large scale, may lead to loss of lives and property and hinder farm accessibility (Jane & Green, 1983; Douglas et al., 1986; Derose et al., 1995; Reid & Page, 2003; Crozier, 2005; Dymond et al., 2006; Brook, 2018). Landslip scars have reduced pasture cover and quality (Douglas, 1986; Derose, 1995; Luckman, 1999) and their revegetation can take almost a century to attain nearly 80% of the unscarred area herbage production (Douglas, 1986; Derose, 1995; Smale et al., 1997; Rosser & Ross, 2011). Douglas et al. (1986) reported scar revegetation was rapid for the first 10 years but slowed down after 30 years in Wairoa hill country. A similar observation in Taranaki hill country was reported by Derose et al. (1995) indicating scars attained nearly 74% of the unaffected area pasture production after 40 years. Derose et al. (1995) attributed the differences in scar revegetation to moisture availability, indicating scars with unlimited moisture availability could attain full recovery after 80 years. As the slope length and elevation increases, the scar size and recovery period increases with likely permanent pasture herbage reduction on slopes greater than 28° (Smale, 1997; Page et al., 2000; Dymond, 2006). The reduction in pasture production can be attributed to loss of fertile top soil, reduced soil water holding capacity and decreased soil depth (Douglas, 1986; Derose, 1995; Smale, 1997; Rosser, 2011). Pain & Stephens (1990) estimated approximately 9.6% loss of pasture lands from landslips on slopes of 20-35° in Taranaki hill country. Derose et al. (1995) reported 10%, 15% and 22% reduction in annual pasture herbage on landslip scars on slopes of 28°, 33-37° and 38-42° respectively from the same area. Douglas et al. (1986) noted pastures on landslip scars had sufficient levels of trace elements needed by livestock but were deficient in foliar nitrogen. This could be due to the dominance of primary and secondary succession native species in the early stages of scar recovery, mainly grass that tolerate low soil nutrients and moisture (Smale, 1997) with legumes increasing as the scar age (Douglas, 1986).

Unlike landslides that occur abruptly, earthflows are slow downslope movement of wet soil (approximately 1 m annually) towards waterways (Zhang et al., 1991; Ministry for the Environment & Stats NZ, 2019) and can be deep (often >10 m) (Basher, 2018) or shallow (<2 m) (Basher, 2013). Deep earthflows occur on slope with elevations as low as 10°, while shallow earthflows are typical in elevations greater than 20° (Basher, 2013; Dymond et al., 2016). Earthflows affect large areas and lead to reduced pasture herbage production through formation of hummocks and low scarps that breakup pasture swaths and damage pasture roots (Taranaki Regional Council, 2018). Depression of more than

80% of pasture production and losses of more than 40% of herbage yields have been reported on rumpled hill country in the Gisborne region (Miller 1991, as cited in Blaschke, 2000). On stabilized old flows, pasture production has been reported to be approximately 10% lower than that of unaffected areas due to changed soil physical properties which limit plant growth (Blaschke, 2000). Termination of earthflows in water ways leads to deposition of large volumes of debris that cause siltation and can lead to obstruction of the drainage system and flooding (Taranaki Regional Council, 2018). The frequency of earthflows can be associated with land use change (Blaschke, 2000; Taranaki Regional Council, 2018; Ministry for the Environment & Stats NZ, 2019), occurring more than two folds in grassed than in forested hill country (Zhang et al., 1993). Earthflows are mainly restricted to the North Island and are the dominant form of erosion in Gisborne and Northland regions (Ministry for the Environment & Stats NZ, 2019)(Figure 5).

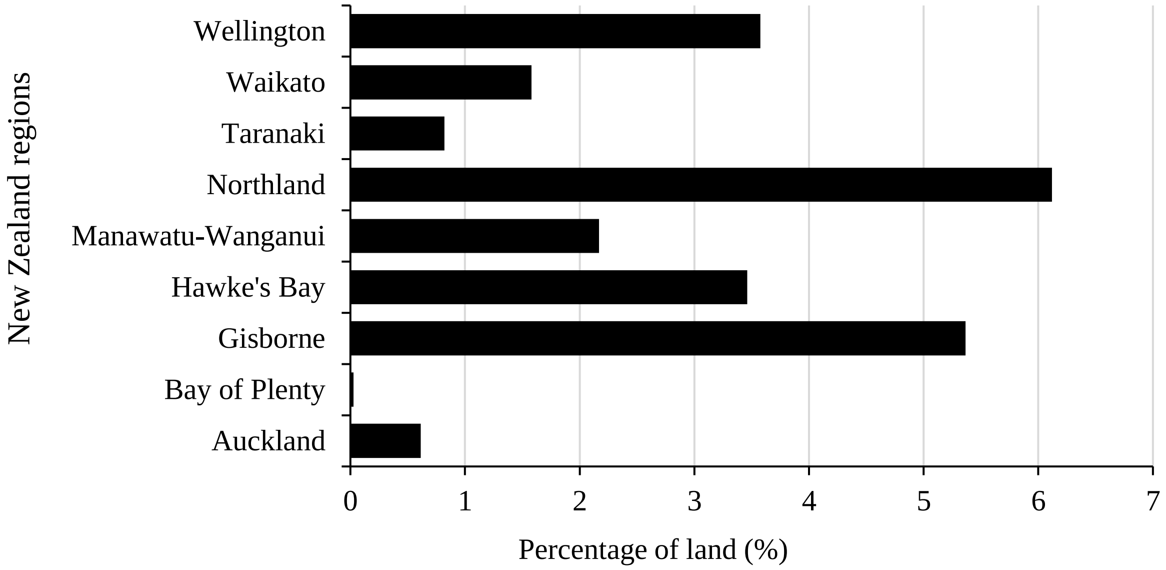

Figure 5. Percentage of land at high risk of earthflow erosion by regions in New Zealand (Data source: https://statisticsnz.shinyapps.io/).

Disparate to mass movement erosions which are triggered by gravity, gullies are caused by running water which scours soil forming channels that are deeper than 30 cm and are the severest form of surface erosion (Karydas & Panagos, 2020). During the formation stage, the channels rapidly widen and deepen and progressively expands upslope before slowing as the gully stabilize to only bank erosion (Blaschke, 2000; Catchments & Creeks Pty Ltd, 2010; Marden et al., 2012; Basher, 2013). Both the open and tunnel forms of gully erosion are common in New Zealand, predominantly in the soft rock hill country in Gisborne and Northland regions (Horizons Regional Council, 2010;

Basher, 2013) (Figure 6). Although gully formation can be initiated by natural forces that cause land instability (Parkner et al., 2007), they are often indicators of misused lands and obliteration of vegetation cover in the farming systems (Blaschke, 2000; Gomez et al., 2003; Marden, 2012; Karydas, 2020).

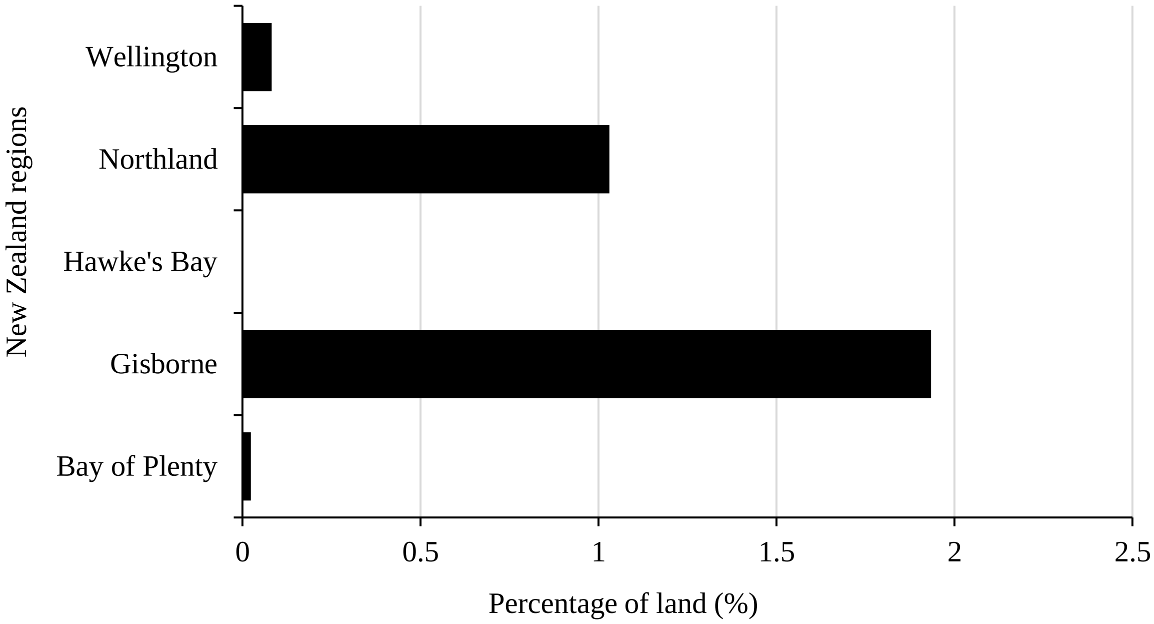

Figure 6. Percentage of land at high risk of Gully erosion by regions in New Zealand (Data source: https://statisticsnz.shinyapps.io/).

Studies in Waipaoa catchment complex in Gisborne, have shown that gully occurrence and expansion was accelerated by the conversion of native vegetation to pasture lands (Derose et al., 1998; Gomez, 2003; Marden et al., 2005a). Like mass movement erosion, gully erosion leads to massive sediment deposition in water ways (Derose, 1998; Hicks et al., 2011; Marden, 2012; Marden et al., 2018a), loss of pasture and productive lands (Horizons Regional Council, 2010). Therefore, it can be construed from the studies results that the major cause of hill country accelerated soil erosion and consequently land and environmental degradation, is conversion of native vegetation to pasturelands.

2.6. Mitigation of Soil Erosion in hill country

The consequences of converting native vegetation to pasture lands on soil erosion was recognized in New Zealand as early as the 1930’s and led to the enactment of the Soil Conservation and Rivers Control Act in 1941 (Cairns et al., 2001; Hocking, 2006; Gregg, 2008; McIvor, 2011; New Zealand Conservation Authority, 2011; Basher et al., 2016). The Act led to the establishment of district catchment boards that were tasked to support and promote experimental, preventative and remedial soil conservation works in their respective districts (Cairns, 2001; New Zealand Conservation Authority, 2011; Basher, 2013). However, several amendments to the Act and reorganization of the local bodies have taken place overtime to meet specific regional soil and water conservation needs (Hocking, 2006; Gregg, 2008; New Zealand Conservation Authority, 2011; Basher, 2016). Although the regions can share similar landscape characteristics, they can differ in geology, soil types, vegetation diversity, climatic condition and anthropogenic influences which determine the dominant type of erosion and hence the mitigation measures to be applied (Cumberland, 1944; Greater Wellington Regional Council, 2006; New Zealand Conservation Authority, 2011).

Soil erosion mitigation measures are aimed at reducing the causes of erosion and enhancing soil resistance to erosive agents (Pollock, 1986; Cairns, 2001) and can be grouped broadly into mechanical and biological methods (Pollock, 1986; Phillips, 2005; Gregg, 2008). Mechanical methods involve construction and change of landscape features and are aimed to supplement where biological measures are not sufficient or applicable (Thompson & Luckman, 1993; Cairns, 2001; Blanco-Canqui & Lal, 2010). Although mechanical structures are highly efficient and give immediate erosion control, they are expensive to construct and maintain (Phillips, 2005). Hence, biological methods are the most widely used due to their low cost and wide alternatives, despite their slow impact on erosion control (Basher, 2013). Nonetheless, biological methods provide lasting self-perpetuating and multiple benefits once established (Phillips, 2005) and will be discussed further since they are more related to the study.

Biological erosion control methods infer to the use of vegetation to protect and stabilize the soil structure (Cairns, 2001; Zuazo & Pleguezuelo, 2008; Gregg, 2008; Basher, 2013, 2016; Zaman, 2018) and the control of animals to reduce the exposure of soil to erosive agents (Hole, 1981; Evans, 1998; Hall et al., 1999). Vegetation can mitigate soil erosion by both mechanical and hydrological mechanisms (Phillips et al., 2012; Lambie et al., 2018). Mechanically, roots reinforce and anchor soil strata by binding soil particles which increases soils' shear strength, the stems and the leaves provide wind and water breaks hence reducing their erosive power, while the weight of the plant exerts more force which couples the soil shear strength (Phillips, 2005; Lambie, 2018). Hydrological mechanisms involve the regulation of soil water content through enhanced water extraction by evapotranspiration and improved soil infiltration capacity due to plant ground cover (Phillips, 2012; Phillips et al., 2015a; Lambie, 2018). There are numerous studies on the use of both exotic and native vegetation in the control of soil erosion in New Zealand hill country (Thompson, 1993; Cairns, 2001; Hawke's Bay Regional Council, 2004; Phillips, 2005; Marden et al., 2005b; Greater Wellington Regional Council, 2006; Hocking, 2006; Gregg, 2008; Douglas et al., 2011; Basher, 2013, 2016; Taranaki Regional Council, 2018; Lambie, 2018).

2.6.1. Use of poplar and willow in erosion control

Polar and willows are some of the most widely used trees in biological erosion control in New Zealand hill country, due to their ease of vegetative propagation, superior growth rate, adaptability to different soil types, extensive root systems and high evapotranspiration rates, which makes them suitable for steep slope and river bank erosion control (Thompson, 1993; Wilkinson, 1999; McIvor, 2006; McIvor & Douglas, 2012; Phillips et al., 2015b; Bay of Plenty Regional Council, 2020). Douglas et al. (2011) reported a 95% reduction in land slip occurrence on 65 sites in Manawatu and Wairarapa when planted with spaced poplar and willows compared to grassed areas, suggesting use of trees as the most feasible soil conservation approach in hill country. McIvor et al. (2015) in their study in Hawke's Bay, observed that the effectiveness of willows and poplars to prevent landslip and gully erosion was increased as the tree diameter at breast height (DBH) exceeded 20 cm and sufficient roots had developed that held the soils firmly. Further, McIvor & Douglas (2012) noted that regardless of the DBH, the spacing of poplar and willows influenced their effectiveness in erosion control and indicated that spacing of approximately 8 m led to earlier and greater soil strata reinforcement. Moreover, Thompson & Luckman (1993) in their study in Gisborne indicated that, more than 40% of ground cover with poplar or willows was needed for successful stabilization of gully and earthflow erosion prone areas. Combined, the results from these studies show the significance of poplar and willows tree age and the need for appropriate spacing and ground cover for successful erosion control. Although poplar and willows belong to the same family and can share similar biological attributes, their clones can differ in environmental requirements and hence their suitability in erosion control (McIvor, 2006). Several studies have proposed use of willows for gully, landslip and stream bank erosions control since they form dense root mats resistant to scouring by surface runoff (McIvor, 2006; Horizons Regional Council, 2014; Phillips, 2015b; Bay of Plenty Regional Council, 2020) while poplars are suggested for hill slope stabilization due to their need for deep and fertile soils (McIvor, 2011; Bay of Plenty Regional Council, 2020). Despite their significance in erosion control in hill country, some poplar and willows clones are reported to be brittle and intolerant to desiccating winds, diseases, drought and poor soil fertility (McIvor, 2006; Horizons Regional Council, 2014; Satchell, 2018; Bay of Plenty Regional Council, 2020). As such, other complementing exotic trees mainly used for plantation forestry such as eucalyptus and pines are also used in erosion control (Thompson, 1993; Wilkinson, 1999; Douglas et al., 2009; Douglas, 2011; Lambie, 2018; Satchell, 2018).

2.6.2. Use of plantation forests in erosion control

Exotic forest plantations are primarily established for timber production and protection of hill country slopes against erosion, with the trees being preferred due to their fast growth rates and adaptability (Phillips, 2012). However, they affect short term erosion control, which diminishes when the trees are harvested, creating a window of vulnerability (Phillips, 2012, 2015a; Satchell, 2018). There are several studies skeptical about the long term erosion control potential of the common plantation forest trees in New Zealand (Marden, 1992; Phillips, 2012, 2015a; Satchell, 2018). Phillips et al. (2012) indicates radiata pine roots take half the time taken by the native trees to start decaying after tree harvesting, with the decayed roots leaving tunnels that are the precursors for mass movement erosion. Satchell (2018) notes that, the short harvesting rotation of radiata pine and their rapid root decay increases the slopes vulnerability to mass movement erosion, suggesting their unsuitability to hill country slopes with high risk of storm induced erosion. Other studies have shown some exotic trees such as eucalyptus produce high levels of allelochemicals that deter revegetation by native plants after the exotic trees are harvested and thus prolongs land exposure to erosive agents (May & Ash, 1990; Narwal, 2000; da Silva et al., 2018). Consequently, several authors have reported the need to look for alternative trees and shrub that are long lived, tolerant to New Zealand diverse environmental conditions, have multiple benefits and without potential to become pests, with proposals to explore the native vegetation (Pollock, 1986; Brooker et al., 1989; Hawke’s Bay Regional Council, 2004; Marden, 2005b; Phillips, 2012; Bergin, 2014b; MacGibbon, 2014; Satchell, 2018; Mackay-smith et al., 2022)

2.6.3. Use of native plants in erosion control

There are over 2000 native tracheophytes of which approximately 80% are endemic and have naturalized to New Zealand environmental conditions (Pollock, 1986; Brooker, 1989; Davis & Meurk, 2001). These abundance of native plant species provides unique and wide selection of plants that can meet various ecological and economic needs (section 2.9). However, there is paucity of information on the role of native plant species in erosion control (Pollock, 1986; Phillips, 2005; Phillips et al., 2011) largely because, the subject is new, focus is on a few species and no long-term studies have been carried out. Pollock (1986) describes some 70 native trees and shrubs species and their potential in erosion control, their locations suitability and propagation and suggest that native shrubs and trees provide a potential wide choice for prevention of all erosion types in New Zealand due to their diversity in growth forms and habits. Marden et al. (2005) studied 12 young primary succession native shrubs found mostly on landslip scars and reported that, although they showed shallow root development in the early stages, native vegetation is diverse and can meet hill slope and riparian restoration and protection. The authors observation were confirmed by modeling results by Phillips et al. (2011) that showed there is a wide variation among young native species in root growth and development, but indicated some species such as Tutu, ribbonwood and cabbage tree were suitable in erosion control. MacGibbon (2014) suggested that a mixed species of native trees and shrubs can be used in riparian erosion control while providing other economic benefits such as timber production. Hawke's Bay Regional Council (2004) noted that, native plants have evolved over centuries on the New Zealand landscape and can provide lasting erosion control compared to the exotic species and provided some native species suitable for mass movement and surface erosion control. Observing from the studies result combined, it can be speculated that native shrubs have a potential in erosion control, but more studies are needed to ascertain their role in hill slope and riparian stabilization.

2.7. Effects of slope on pasture production in hill country

Hill country occupies approximately 4 million hectares and supports more than 50% of the sheep and beef farms in New Zealand (Kemp, 2016). Hill country is characterized as having slopes above 15° and is considered to cover classes 4 to 7 in the LUC system (Lynn, 2009). However, hill country farms contain a mixture of slopes, ranging from flat to steep (Saggar et al., 2015), resulting in pasture production variability on different sites within a farm (Chapman & Macfarlane, 1985; López et al., 2003). The variation in pasture production results from differences in soil properties and microclimate due to the influence of both slope gradient and aspect. Slope gradient modifies soil drainage and erosivity therefore affecting soil depth, texture, organic matter accumulation and nutrient turnover (Penny et al., 2016). Slope aspect is determined by land orientation and affects the amount of solar radiation and rainfall received and the rate of evaporation experienced on a slope face (Radcliffe, 1982). Slope gradient and aspect are thus the main topographical factors that determine pasture composition and production on hill country (Radcliffe, 1982). Due to the impact of season, there is a similar pasture growth profile across hill country in the various regions in New Zealand (Figure 7).

Pasture production studies in New Zealand hill country are somewhat inconsistent in the grouping of slope gradient into categories (Table 4). Long term studies in the Manawatu region reliably use slope gradients of 0 to 12° (low), 13 to 25° (medium) and >26° (high) (López, 2003; Saggar, 2015; Kemp, 2016), which are comparable with easy, moderately steep and steep gradients respectively (Praat, 2011). However, the studies result agree on a decreasing herbage mass with increasing slope gradient.

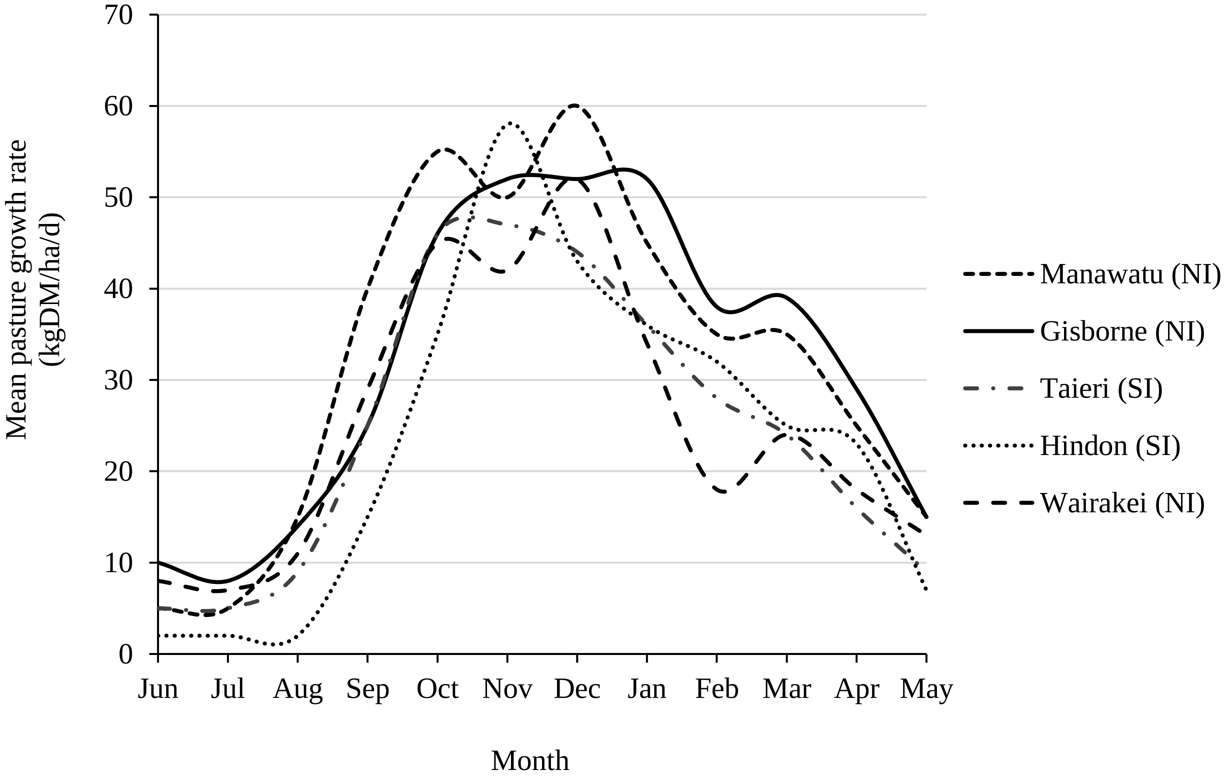

Figure 7. Typical mean pasture growth rate on hill country in the North and South Islands (Data source; 2011 Farm Technical Manual, Lincoln University)

Table 4. Slope gradient categories used in pasture production studies in New Zealand hill country.

Slope description	Slope gradient (°)	Pasture Growth Attributes			Author
		Yield (kgDM/ha/y)	Estimated Growth (Rate/d)	% Change	
Low	0-12	12568	34.4	100.0	López et al. (2003) Kemp & Lopez (2016)
Medium	13-25	5806	15.9	46.2	
High	>26	4003	11.0	31.9	
Low	0-12	13803	37.8	100.0	Lambert et al. 2014
Medium	13-25	10188	27.9	73.8	
High	>26	9050	24.8	65.6	
Low	0-12	14072	38.6	100.0	Lambert et al. 1983
Medium	13-25	10857	29.7	77.2	
High	>26	8164	22.4	58.0	
Stock camp		25000	68.5	100	Chapman & Macfarlane, (1985)
Steep		5000	13.7	20	
Flat	0-15	9425	25.8	100.0	New Zealand Landcare Trust (2011)
Easy	0-25	8338	22.8	88.5	
Moderate	15-25	7250	19.9	76.9	
Steep	>25	4350	11.9	46.2	

2.8. Poplar and willow browse as a source of supplementary fodder

Poplar (genus *Populus*) and willow (genus *Salix*) occur naturally in the northern hemisphere but are exotic in New Zealand (Wilkinson, 1999; McIvor, 2006). The genera are closely related, easily propagated vegetatively and both have tree and shrub growth forms (Wilkinson, 1999). They were initially introduced in New Zealand for soil conservation, windbreak and shelterbelts on hill country and have gradually became a source of supplementary fodder during dry summer seasons (Wilkinson, 1999; Hussain et al., 2009). Each genus has several species from which hybrids are bred and their clones propagated to meet various economic, environmental and farming needs in New Zealand (Wilkinson, 1999; McIvor, 2006). The recommended poplars for fodder in New Zealand are, *Populus deltoides x nigra* clones (Flevo, Tasman, Veronese and Argyle), while willows are *Salix matsudana* (Tangoio) and *S. schwerinii* (Kinuyanagi), because they are productive, palatable and withstand heavy pruning (McIvor, 2006).

In pastoral farming systems, livestock obtain poplar and willow fodder from leaf fall and pollarded herbage in widely spaced trees/shrubs and alternatively from coppiced or browsing close planted fodder blocks (Douglas et al., 2003; McWilliam et al., 2005b). Pollarding is used to limit tree height at approximately 1.5 m above ground to promote dense leafy branches that are browsed to supply fodder during pasture scarcity and differs from coppicing where tree growth is maintained to near the ground level and fodder regularly harvested and carried to animals (Douglas, 2003; McIvor, 2006). The fodder consists of leaves and soft stems. Sheep are able to eat soft stems up to 7 mm and cattle soft stems up to 10 mm diameter (Moore et al., 2003; Jones & McIvor, 2013). Kemp et al. (2001) reported edible forage yields of approximately 22.4 kg DM/tree and 18.0 kg DM/tree in widely spaced 10 year old Tongoio willow and Veronese poplar respectively while Jones & Mcivor (2013) indicated that up to 7t DM/ha of edible fodder can be obtained from five year old densely planted fodder blocks. Although nutritive value of edible portions of poplar and willow fodder are comparable (Kemp et al., 2003; McWilliam, 2005b), willows yield more DM and higher concentration of nonnutritive secondary compounds (McWilliam, 2005b; New Zealand Poplar and Willow Research Trust, 2013).

2.8.1. Poplar and willow fodder nutrients content

The nutritive value of poplar and willow fodder is superior than that of dry pastures (Kemp, 2001; McWilliam et al., 2004; Jones, 2013) and can provide sheep and cattle nutrients above their maintenance requirements during dry summers (Douglas et al., 1996; Moore, 2003; New Zealand Poplar and Willow Research Trust, 2013). However, the fodder nutrient composition of the two genera can vary by species, clone, age, location and season (McCabe & Barry, 1988; Kemp, 2003; McWilliam, 2004).

Results from various studies report crude protein (CP) (Figure 8) for the edible portion (leaves plus stems less than 7 mm) of poplar clones in the range of 12 to 19% of DM with a mean of 14.9% (Kemp, 2001) and between 7 and 18% for willow clones with a mean of 14.2% (Kemp, 2001). Crude protein is highest during the spring than the summer season for both poplars and willows, while Veronese and Tongoio clones have the highest CP for poplar and willow respectively (Kemp, 2001, 2003; McWilliam, 2004; Jones, 2013). These results demonstrate the differences in CP content among the poplar and willow clones, which can have implication on use of the clones to feed livestock.

Reported metabolizable energy (ME) for poplar and willow (Figure 9) clones are similar and range between 8.9 to 11.4 MJ/kg DM. The range of ME for different clones, e.g. Veronese (Kemp, 2001, 2003; McWilliam, 2004, 2004) and Tasman (Kemp, 2001; McWilliam, 2004) poplars and Tongoio (McCabe, 1988; Kemp, 2003; Moore, 2003; McWilliam, 2005b) and Kinuyanagi (Oppong et al., 2001; Kemp, 2003) willows, are similar and shows less variation than CP among clones and seasons.

Results of studies on poplar report ash contents ranging from 7.3 to 9.3% DM (Kemp, 2003; McWilliam, 2004, 2005b) similar to willow which range from 5.4 to 8.7% DM (Kemp, 2003; Moore, 2003; McWilliam, 2004; Pitta, 2007; Pitta et al., 2007; Mupeyo et al., 2011) with the exception of Kunuyanagi which has lower ash other species (Kemp, 2003). These studies show that ash content is higher in summer (Kemp, 2001, 2003; McWilliam, 2004) than in spring (Kemp, 2003) in both genera and willow leaves have higher zinc and magnesium and lower sodium compared to poplar (New Zealand Poplar and Willow Research Trust, 2013) but higher than in pastures (Douglas, 1996; Taranaki Regional Council, 2016). Additionally, crude fibre (CF) content for the two genera are comparable, with a mean of 39.5% DM reported for neutral detergent fibre (NDF) and a range of 26 to 34% DM for acid detergent fibre (ADF) (McCabe, 1988; Kemp, 2003; Moore, 2003; McWilliam, 2004; Pitta, 2007).

Most studies have found higher organic matter digestibility (OMD) for both genera in the spring season than summer with Kemp et al. (2003) reporting 77.9 and 78.6% DM for the spring season and McWilliam (2004b) reporting 66% DM, similar to 65.1 and 68.7% DM reported by Kemp et al. (2003) for summer. Comparing summer and autumn, McWilliam, Barry, & López-Villalobos (2005) reported a higher OMD in summer for Veronese poplar and Moutere willow but observed that the autumn decline was much lower than that reported for grass-based pastures. Similar results were reported for Tongoio and Kinuyanagi willow by Oppong et al. (2001). The decrease in OMD from spring through autumn is expected in deciduous plants as lush foliage emerges in the spring and ages to senescence and fall in the autumn (McWilliam, 2005a).

Poplar and willows contain higher concentration of secondary compounds (lignin, condensed tannins (CT), salicin and other phenolic glycosides) than pastures (Douglas, 1996; Moore, 2003; McWilliam, 2005b) and herbaceous legumes (Oppong, 2001), but the concentration differs with clones and is highest in willows (Jones, 2013). Although secondary compounds negatively affect fodder voluntary intake and digestibility (Jones, 2013), sheep and cattle adapt within short period and increase both intake and the diameter of digestible portion of the fodder eaten (Oppong, 2001; Moore, 2003; McWilliam, 2005a; Douglas et al., 2006; Pitta et al., 2009). Finding from various studies have reported benefits in sheep from secondary compounds in poplar and willow. CT have been shown to reduce rumen microbial degradation of plant proteins, hence increasing protein (McWilliam, 2004) and amino acids (Pitta, 2009) absorption which is associated with reduced live weight loss during drought and improved reproductive performance in sheep (McWilliam, 2004; Pitta, 2009). The CT have also been reported to reduce helminths load in sheep, improving their health and liveweight performance (Lira, 2008; Mupeyo, 2011).

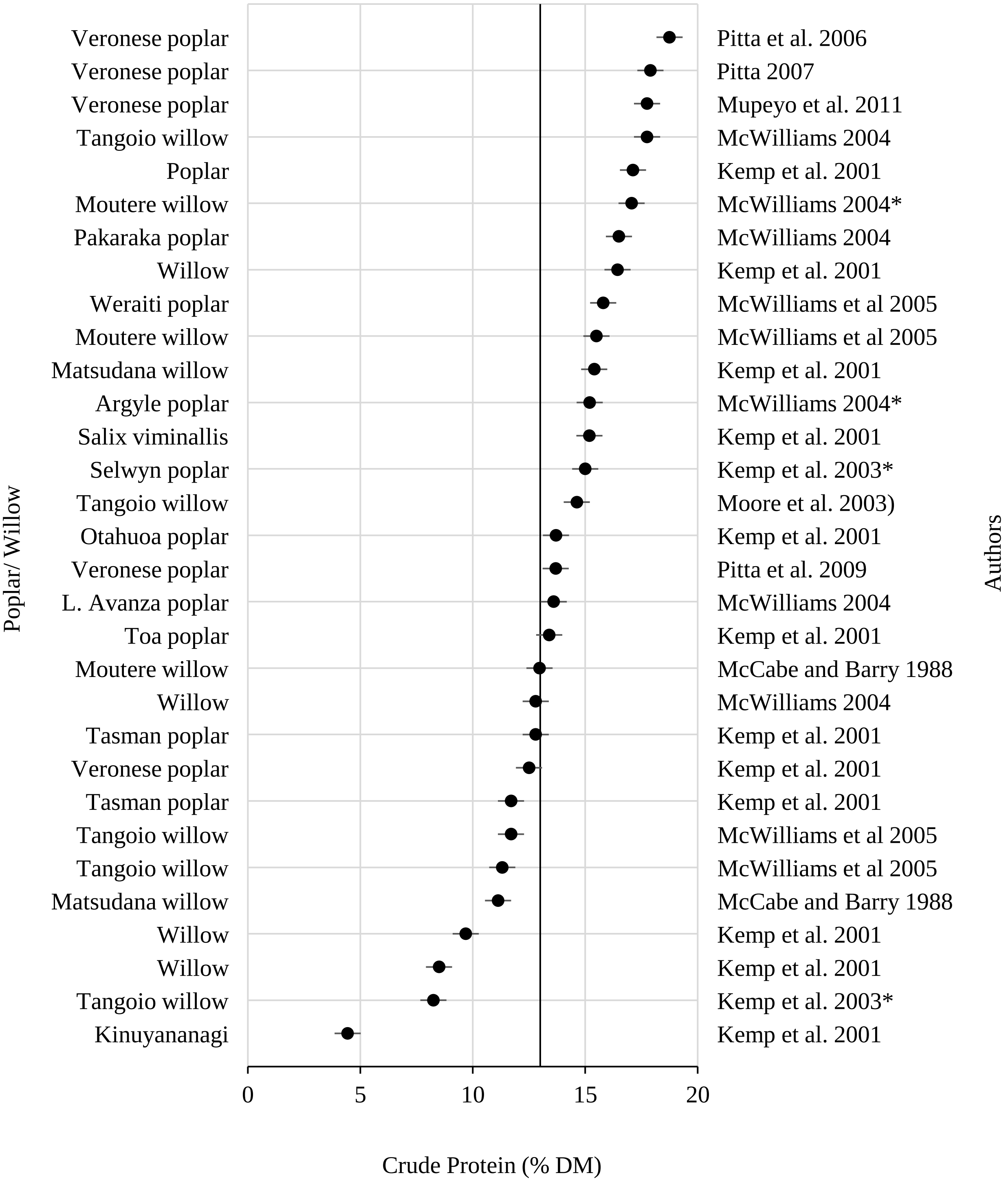

Figure 8. Crude protein of edible fraction (leaf + stem <7 mm) for various willow and poplar clones reported by various authors in New Zealand. Kemp et al. 2003* (cross reference from Douglas (pers. comm) 2003) and McWilliams 2004* (cross reference from Smith 1992).

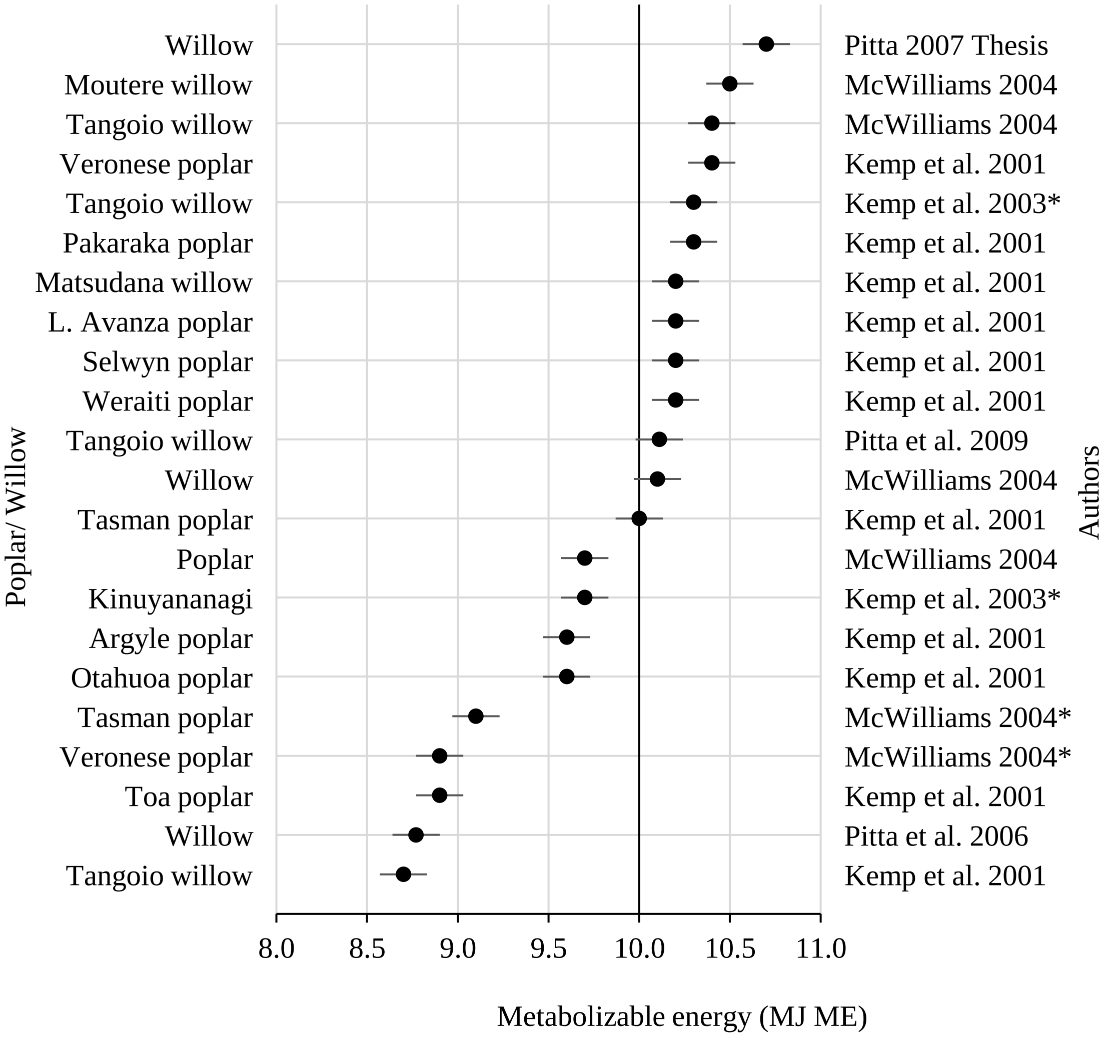

Figure 9. Metabolizable energy of edible fraction (leaf + stem <7 mm) for various willow and poplar clones reported by various authors in New Zealand. Kemp et al. 2003* (cross reference from Douglas (pers. comm) 2003) and McWilliams 2004* (cross reference from Smith 1992).

2.9. New Zealand Native Shrubs

The expansion of pasturelands and over harvesting of native vegetation reduced indigenous forest from more than 80% to the currently less than 25% of New Zealand land cover (Allen, 2013; Bergin, 2014b; Kerr & Stewart, 2014). Over 80% of the native vegetation are endemic to New Zealand (Brooker, 1989; Dickinson et al., 2015) and more than 80% are in conservation forests (Allen, 2013; Industry, 2020). The native shrubs account for approximately 16% of the indigenous fauna with approximately 400 species (Merrett, 2006; Kerr, 2014) distributed in isolated remnants throughout New Zealand (Davis, 2001), most of which are in the un-utilizable areas in hill country (Dodd, 2007; Quinlan et al., 2014). The native shrubs are adapted to various ecological conditions and have numerous environmental, socio-cultural and economic uses (Brooker, 1989).

2.9.1. Uses of Native Shrubs

Native shrubs provide direct and indirect benefits and for long-term have been used for cultural and spiritual purposes and as sources of raw materials for crafts, food, building and indigenous medicines (Brooker, 1989; Dodd, 2007; Bergin, 2014a). Their potential use in environmental management have received attention recently, with studies documenting their roles in biodiversity restoration (Dodd, 2007; Bergin, 2014a; Quinlan, 2014), carbon sequestration (Kimberley et al., 2014; Ministry for Primary Industries, 2017), and soil and water conservation (Dodd, 2007; Bergin, 2014a; MacGibbon, 2014; Quinlan, 2014). Several studies findings have also suggested the suitability of native shrubs in reclaiming and utilizing marginal pastoral land that are too steep, slip and erosion prone or too wet to drain, since they are well adapted to the New Zealand soils and climatic conditions (Pollock, 1986; Lambert et al., 1989a; Marden, 2005b; Dodd, 2007; Bergin & Kimberley, 2014).

The presence of mixed native species on a farm improves the landscape aesthetics (Dodd, 2007; Bergin, 2014) and when planted in rows can be used as shelter belts for livestock (Lambert, 1989a; Dodd, 2007). Their diversity in growth forms and florescence makes them attractive and are commonly used in recreation and home gardens (Dodd, 2007; Bergin, 2014). Native shrubs are reported to be excellent sources of pollen and nectar for honey bees (Sluys & Newstrom-Lloyd, 2009), since many species blossom during late autumn through late spring (Southern Woods, 2012), have high pollen protein (Newstrom-lloyd et al., 2020) and some species such as Manuka contain medicinal organic compounds that makes the honey superior (Mcpherson, 2016).

Despite the numerous benefits and environmental services provided by native shrubs, their potential use as a supplemental source of fodder for livestock have not been widely explored. However, studies on diet preference for introduced wild herbivores in New Zealand forest indicate some native shrubs can be a potential source of fodder for livestock. Nugent (1990) reported that fallow deer regularly consumed *Griselinia littoralis, Coprosma* spp, *Pseudopanax* spp and *Nertera* spp, with *G. littoralis* contributing more than 23% of their diet in the Blue Mountain Forest. Similar results were reported for the red deer in Wihaha forest where more than 36% of their diet comprised of *G. littoralis* and *Pittosporum crassifolius* (Nugent et al., 2001). Studies on feral goat on Mt Taranaki forest showed *Asplenium bulbiferum, Astelia* spp. *Coprosma grandifolia, G. littoralis, Melicytus ramiflorus, Rpogonum scandens* and *Weinmannia racemose* were the commonly browsed and *A. bulbiferum* and *R. scandens* formed bulk of their diet (Mitchell et al., 1987). Results from a study examining the diet of feral goats and pigs on Auckland island, reported woody plants comprised approximately 41% with *Metrosideros umbellate, C. foetidissima* and *P. simplex* consumed by more than 76% of the goats (Chime et al., 1995). While studying diet preferences of fallow, red and white tailed deer and feral goats, Forsyth et al. (2002) indicated that *G. littoralis, M. ramiflorus, P. arboreus, Schefflera digitata,* and *W. racemose* were the most preferred and present in their diets. The diet preference by the wild ungulates is influenced by the season and native plant species abundance, palatability (Mitchell, 1987; Nugent, 2001; Forsyth, 2002; Kerr, 2014) and nutrient level (Forsyth, 2002, 2005).

2.9.2. Native Shrubs Fodder Nutritive Value

Studies profiling native shrubs nutrient content are few and scanty compared to those for the exotic species in New Zealand. Studies on *M. ramiflorus* have reported CP of approximately 13.6% (Williams, 1982), 16% (Christa et al., 2015) and 13.1% (Dewhurst, 2012) and for *G. littoralis* approximately 4.8% (Dewhurst, 2012), 6.1% (Simmonds, 2020) and 6.5, 6.6 and 7.1% (Körner et al., 1986). The estimated CP from foliage nitrogen concentration for Manuka (*Leptospermum scoparium*) and Tauhinu (*Ozothamnus leptophyllus*) was approximately 9.4 and 7.5% respectively (Lambert, 1989a) and 9.1% for *Coprosma robusta* (Lee & Johnson, 1984; Dewhurst, 2012). Simmonds (2020) reported CP for *Hoheria populnea* leaves of approximately (11.1%), *P. arboreus* (5.3%), *P. crassifolium* (6.8%), and *C. repens* (8.0%). On average the CP reported for native shrubs was lower to that reported for willow and poplar fodder (Kemp, 2001, 2003; Jones, 2013) (Figure 10).

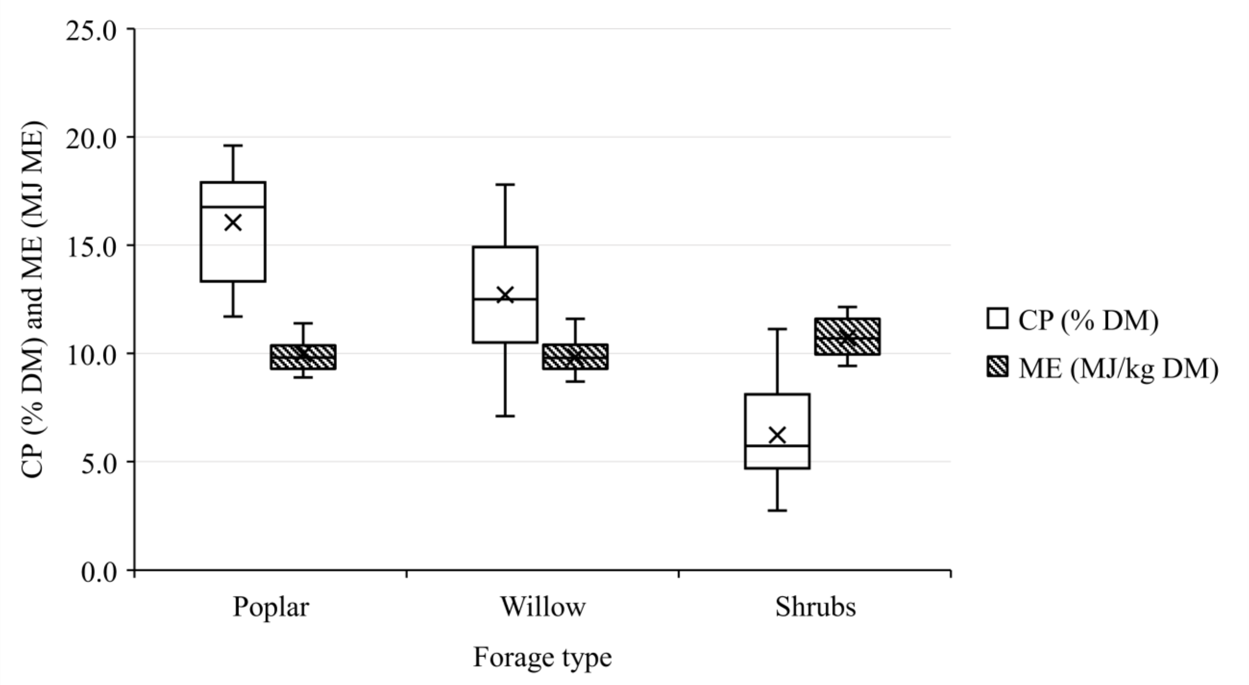

Figure 10. Comparison of the crude protein (CP, % DM) and Metabolizable energy (MJ, ME/kg DM) between native shrubs and exotic species (Poplar and willow). The height of the box indicates dispersion (lower and upper quartile), whiskers the spread (minimum and maximum) and x the mean for CP and ME.

Williams (1982) reported metabolizable energy (MJ/kg DM) of approximately 11.7 for *M. ramiflorus*, and Simmonds (2020) reported approximately 11.0 for *H. populnea* leaves, *G. littoralis* (11.7), *P. arboreus* (12.2), *P. crassifolium* (11.3), and *C. repens* (11.7) which were relatively higher than reported for poplar and willow (Kemp, 2001, 2003; Oppong, 2001; Moore, 2003; McWilliam, 2004) (Figure 10).

Neutral detergent fibre (NDF) reported by Simmonds (2020) for native shrubs leaves ranged from 21.3 to 39.9% and was highest in *H. populnea* and lowest in *P. arboreus* but comparable to that reported for willow and poplar (Kemp, 2003; Moore, 2003; McWilliam, 2004; Pitta, 2007) (Figure 11). The organic matter digestibility (OMD) reported for native shrubs by Simmonds (2020) was highest in *P. arboreus* (82.5%), *C. repens* (80.1%), and *G. littoralis* (80.0%) and lowest in *H. populnea* (76.8%) and on average relatively higher compared to that reported for willow and poplar (Kemp, 2003; McWilliam, 2005a) (Figure 11).

Except for *G. littoralis* (12.0%), the reported lignin (Figure 12) levels of native shrubs was on average (10.1%) (Simmonds, 2020) and lower than reported for willow (13.6%) and poplar (11.8%) (Douglas, 1996; Moore, 2003; McWilliam, 2005a). Ash was higher (7.4%) (Simmonds, 2020) than reported for willow (6.4%) but lower than that of poplars (8.3%) (Kemp, 2003; McWilliam, 2004; Pitta, 2007; Mupeyo, 2011), except for *H. populnea* (11.7%) (Simmonds, 2020) which was higher than in poplar and willow but comparable to ash reported for *M. ramiflorus* (10.7%) (Williams, 1982) (Figure 12).

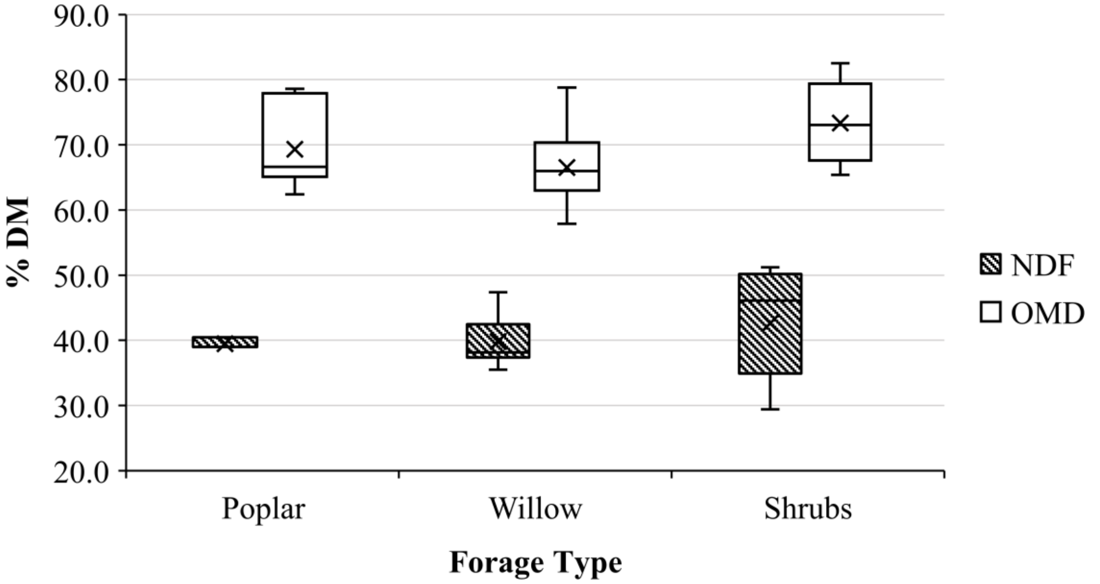

Figure 11. Comparison of the neutral detergent fibre (NDF, % DM) and organic matter digestibility (OMD, % DM) between native shrubs and exotic species (Poplar and willow). The height of the box indicates dispersion (lower and upper quartile), whiskers the spread (minimum and maximum) and x the mean for NDF and OMD.

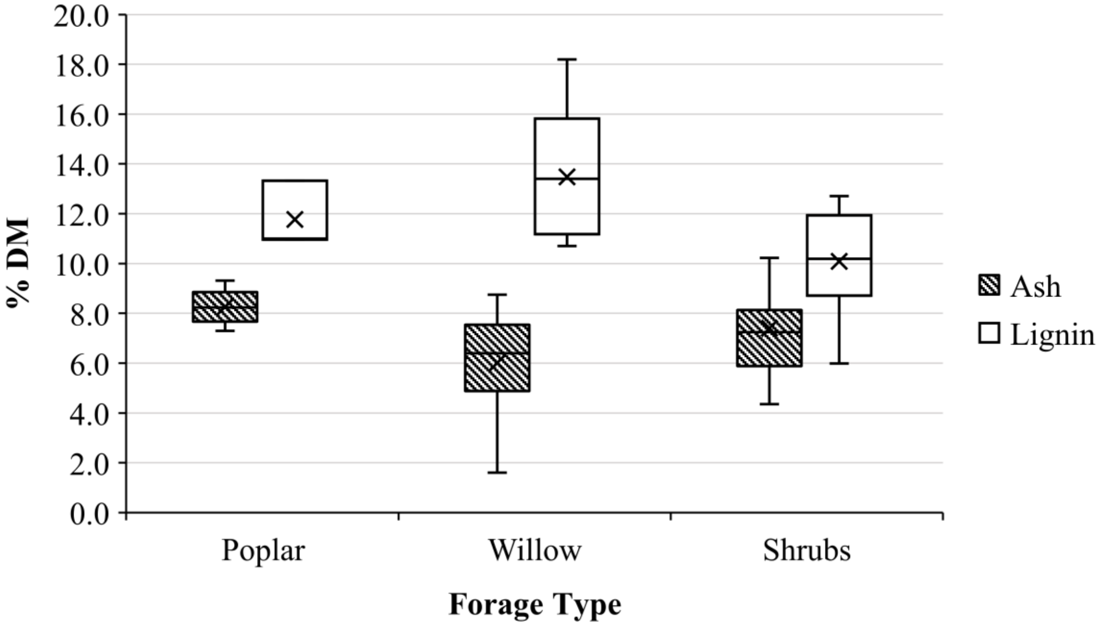

Figure 12. Comparison of the ash (% DM) and lignin (% DM) between native shrubs and exotic species (Poplar and willow). The height of the box indicates dispersion (lower and upper quartile), whiskers the spread (minimum and maximum) and x the mean for ash and lignin.

2.9.3. Native Shrubs Carbon Sequestration and Biomass Accumulation

The carbon cycle is a biogeochemical process through which carbon is continually transformed, exchanged, and stored as carbon stocks. Carbon stocks have been defined as a reservoir or system with the capacity to accumulate or release carbon with the atmosphere, large water bodies, soil and forests as the major reservoirs (FAO, 2004). Carbon leaves the atmosphere by dissolving in large waterbodies and through photosynthesis where plants make organic compounds that are transferred along the food chain. It is released back to the atmosphere through biota respiration and decomposition, fossils combustion, geological processes, and diffusion from water bodies.

Globally, forest carbon stocks are distributed approximately, 55% in the tropical, 32% in boreal and 14% in the temperate forests (Pan et al., 2011). Woody vegetation is the major driver of carbon sequestration and provides a long- term biological carbon sink (Ma et al., 2018). According to New Zealand Ministry for Primary Industries (MPI), forests exclude fruit and nut trees and refer to an area that is at least one hectare in size with a width of not less than 30m that is occupied by woody vegetation capable of reaching heights of more than 5m and form crown cover greater than 30% (Ministry for Primary Industries, 2015). The carbon sequestered by forests is finite and is influenced by the geographical location, climate, dominant woody species, soil type, forest age and management practices (Ministry for Primary Industries, 2017; Ma, 2018; Truax et al., 2018; Gaudel, 2019).

The bulk of New Zealand carbon stocks are reserved in indigenous forests (85%) with the remainder in the exotic forests (10%) and regenerating indigenous forests (5%) (Beets et al., 2014b). Carbon stocks in forest systems can broadly be partitioned into; live organic matter consisting of the above (stem, foliage and branches) and below (roots) ground biomass, dead organic matter (litter and dead wood) and soil (mineral, organic and peat) carbon (FAO, 2010). Although proportionate distribution of carbon stock varies with forest systems (Ma, 2018), approximately 42% is apportioned to the live organic matter (Pan, 2011; Gaudel, 2019).

The New Zealand Ministry for Primary Industry (MPI) have calculated the carbon sequestration potential for common forest species in New Zealand and estimated the regional carbon stock capacities by forest type and age (Figure 13) (Ministry for Primary Industries, 2017). While using *Pinus radiata,* MPI showed that, for each species the carbon stock varies with geographical location (Figure 14) and the rate of carbon sequestration is highest in fast growing exotic, compared to indigenous species (Figure 13) (Ministry for Primary Industries, 2017).

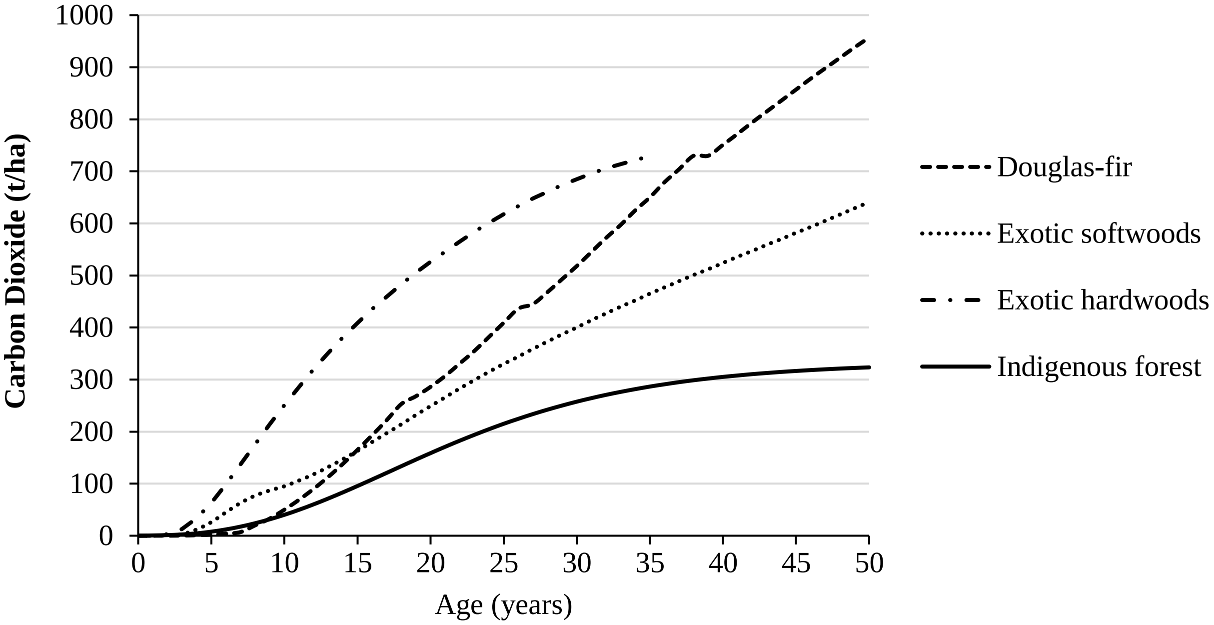

Figure 13. Average carbon stock for common forest trees in New Zealand. Data Source (Ministry for Primary Industries, 2017)

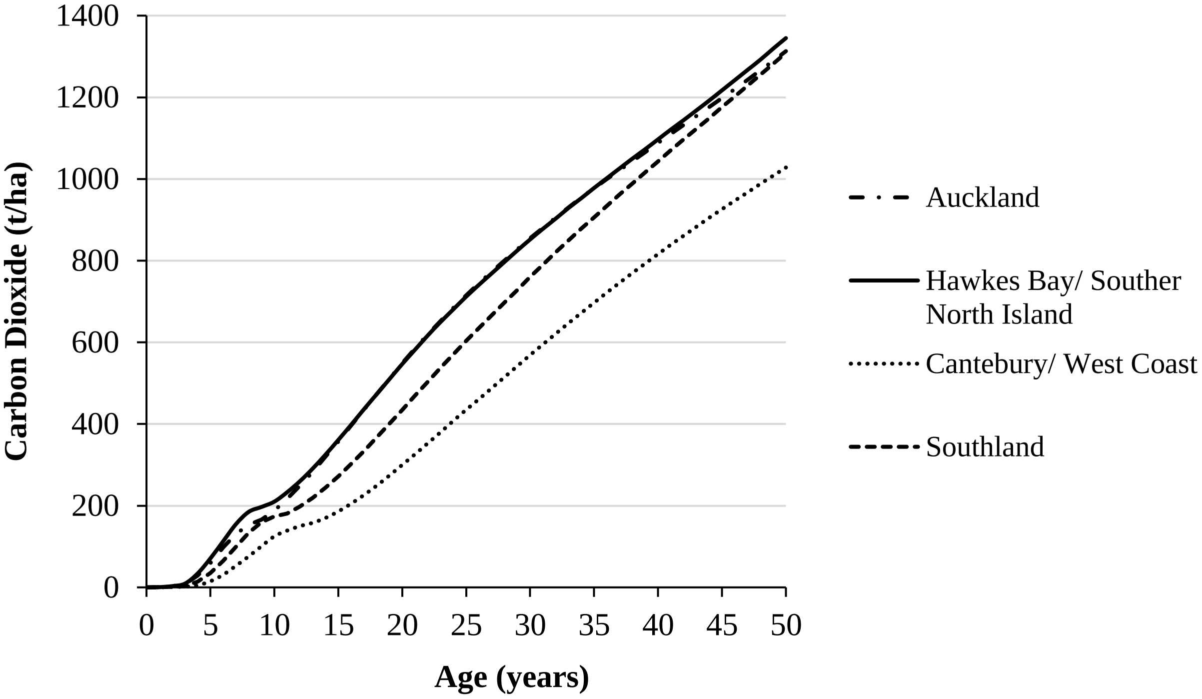

Figure 14. Average carbon stock for Pinus radiata growing in different regions in New Zealand. Data Source (Ministry for Primary Industries, 2017)

2.9.4. Native shrub foliage biomass

Approximately 80% of the total live organic matter in woody vegetations is commonly assumed to be above-ground biomass (Marden, 2005b; Marden et al., 2018b; Poorter et al., 2012a; Kimberley, 2014). However, the biomass distribution is influenced by woody vegetation factors (species and age) and limiting resources (light, nutrients and space) (Marden, 2005b; Poorter, 2012a; Irving, 2015; Ma, 2018) that are determined by the stocking density (Truax, 2018).

Results for studies on 12 common native shrubs in New Zealand reported distribution of approximately 30% of live organic matter to below-ground biomass by their fifth year of growth (Marden, 2005b). A study of eight common indigenous conifers and broad leafed trees in New Zealand reported approximately 20 to 50% of above-ground biomass was distributed to foliage biomass and concluded the apportioning was dependent on age and species (Marden, 2018b). Poorter et al. (2012) observed that indigenous conifers distributed more above-ground biomass to foliage but similar below-ground biomass to the broad-leafed indigenous trees. While studying the exotic species, Kemp et al. (2001) and Oppong et al. (2002) reported edible foliage biomass for willow and poplar ranged from 50 to 65% and increased with age.

Tree spacing studies have demonstrated that increasing planting density increased competition for light, space and soil resources affecting allocation of biomass to below and above-ground compartments (Truax, 2018). High planting densities accelerates soil resources depletion that triggers increased biomass allocation to below-ground to maximize nutrients absorption especially in fast growing exotic trees such as poplar (Truax, 2018). Increased competition for light with increasing density and age enhances self-pruning in light sensitive woody plants and senescence of shaded leaves in shade tolerant plants, which increases the above-ground biomass distribution to the stem than in branches and foliage (Fang et al., 2007). Poorter et al. (2012) indicated stems and branches can account for approximately 95% of the above-ground biomass allocation in mature and full canopy closure forests. The response to light have been demonstrated in poplar, where, trees under high light availability developed large and deep crowns compared to small and shallow crowns in space limited stands (Xue et al., 2012; Truax, 2018). The rate of above-ground biomass allocation to foliage decreases with age regardless of stocking density (Fang, 2007; Xue, 2012; Beets, 2014b) and a similar behaviour would be expected to be heightened in native shrubs noting their dense and deep crowns due to their multi-stemmed physiognomy.

2.9.5. Native shrub fodder yields

Fodder yield estimation methods can be grouped either as destructive or non-destructive (López-Díaz et al., 2011; Louhaichi et al., 2018). The destructive method involves harvesting part or the entire shrub and weighing the different components (López-Díaz, 2011; Conti et al., 2013; Beets, 2014b; Salas Macías et al., 2017). This method provides accurate yield estimates for individual shrub which can be extrapolated to estimate fodder yields in uniform plantations (Kemp, 2001; López-Díaz, 2011; Salas Macías, 2017). However, destructive method are expensive, laborious and unsuitable for threatened species and heterogenous shrubs (López-Díaz, 2011; Salas Macías, 2017). To avert these limitations, non-destructive methods that utilize *in situ* observations, measured or remotely sensed data are applied to predict fodder yield estimates (López-Díaz, 2011; Beets, 2014b; Salas Macías, 2017; Louhaichi, 2018). Allometric models are the most commonly used nondestructive method because they can relate plant variables (Kemp, 2001; Picard et al., 2012; Xue, 2012; Beets, 2014b; Easdale et al., 2018; Marden, 2018b). Picard et al. (2012) pointed out that, different dimensions of a plant are statistically related and can be used to predict each other and Easdale et al. (2018) and Conti et al. (2013) proposed that using species specific allometries give more accurate predictions.

Mason et al. (2014) reported that shrub specific allometric models using basal area and height accurately (R^2=0.93) predicted the dry matter for invasive shrubs in New Zealand. Marden et al. (2018) compared root collar diameter (RCD) and diameter at breast height (DBH) for eight indigenous trees in New Zealand and suggested that RCD was a better predictor of height and above-ground biomass and was not limited by the tree height. Studies on poplar and willow showed that allometric models using branch diameter suitably predicted branch forage yields and edible dry matter (Kemp, 2001) and DBH accurately predicted edible dry matter in willow (R^2=0.97) and poplar (R^2=0.88) trees (Kemp, 2003). Conti et al. (2013) further suggested that, due to the physiognomic difference between trees and shrubs, every stem should be considered as an individual tree to avoid underestimation of predicted forage dry matter in shrubs. However, there are limited studies that define specific native shrubs allometry due to their diversity, compared to exotic trees and shrubs utilized in New Zealand.

2.10. Modelling in Agricultural System

A system can be defined as a collection of components within a known boundary that interact and work together as a whole (Spedding, 1988). Therefore, an agricultural system is a composite of biophysical, social and economic components that interact and influence the manipulation of natural resources for food, feed, raw materials and income (Drinkwater et al., 2016; Ahmed et al., 2020). The interaction of the agricultural system components have resulted in evolution of farming systems over time (Caldwell, 2000). A farming system is a group of similar farm systems (McConnell & Dillon, 1997; Stevens et al., 2016; Jones et al., 2017), which are the decision-making units made up of the households, cropping and livestock sub-systems that interact and transform resources into outputs for subsistence and income (Fresco & Westphal, 1988; Woodward et al., 2008). The sheep farming systems in New Zealand are briefly described in Section 2.2.

Farm systems have multiple objectives and are often faced with decisions making on how to sustainably utilize available resources subject to constraints to meet the objectives (Glen, 1987). The decision-making process can be simple, only requiring intuitive reasoning at the household level or multifaceted thereby demanding multi-disciplinary system modelling, research and statistical support (Glen, 1987; Caldwell, 2000). System modelling denotes the process of designing, building and using models, which are an abstraction of reality or a system (Motta & Pappalardo, 2013). System modelling supports complex decision-making and offer solutions to challenges by providing insights on the interactions of the farm systems components and their output (Guillem et al., 2015). Various models are used in agricultural system and can be broadly grouped into biophysical, conceptual and mathematical models (McConnell, 1997; Dourado-Neto et al., 1998; Alexander, 2003; Motta, 2013). Although distinct, the models complement each other and have their own advantages and disadvantages in the modelling process (Alexander, 2003).

Physical models are constructed prototypes used to represent a system or its components (Dourado-Neto, 1998; Alexander, 2003; Motta, 2013) and are commonly used in landscape, agricultural biomechanical modelling (Koehl, 2003) and in some instances to check the results of a mathematical model (Alexander, 2003). Conceptual models are diagrammatic or graphical representation of a system, its components and the relationships among them and are used in agricultural system for illustrations and providing foundation for development of physical and simulation models (Bozlu &

Demirörs, 2008; Robinson, 2011; Motta, 2013; Robinson et al., 2016). Unlike the physical and conceptual models which are qualitative, and components and their relationships can be visualized, mathematical models quantitatively describes these relationships using equations and functions (France, 1988; Alexander, 2003; Torres & Santos, 2015). Mathematical models are hugely used in agricultural systems and will be discussed further.

2.10.1. Classification of Mathematical Models

The components of an agricultural system follow underlying principles that can be described and their interactions defined using mathematical models (France, 1988; Woodward, 2008; Moghadas & Jaberi-Douraki, 2019). Mathematical models can be grouped either as dynamic or static, deterministic or stochastic, empirical or mechanistic and discrete or continuous depending on the model structure and the relationship between the dependent (objective) and independent (decision) variables (France, 1988; Tedeschi et al., 2005; Stygar & Makulska, 2010; Moghadas, 2019; Ahmed, 2020) (Appendix 1). Dynamic models describe time dependent relationships while static models are instantaneous representing the system relationships at a particular moment (France, 1988; Stygar, 2010; Black, 2014; Sherif et al., 2019; Ahmed, 2020). The effect of time in dynamic models can either be seamless where a system can change behavior at any moment as described by continuous models or can assume integer values where system changes behavior at distinct interval as described by discrete models (Tedeschi, 2005; Moghadas, 2019). Predictions in deterministic models are not associated with randomness and a set of decision variables produces the same solutions. Conversely, stochastic models variables have a probability distribution and a set of variables elicit random behavior in the system (France, 1988; Tedeschi, 2005; Sherif, 2019; Ahmed, 2020). Whereas empirical models describe variable relationship based on data from experiments and observations, mechanistic models are built on scientific theories and concepts and are hierarchically aggregated to explain system behavior (France, 1988; Tedeschi, 2005; Stygar, 2010; Black, 2014; Sherif, 2019; Ahmed, 2020).

Consequently, static and empirical models are used to describe the behavior of a system and are often used in optimization programming while dynamic and mechanistic models can explain observed changes in the behavior of a system and are commonly applied in simulation modelling (France, 1988; Tedeschi, 2005; Black, 2014). As such, mathematical models can be used as tools to explore solutions and determine interaction among components in agricultural system (Flichman, 2011). The commonly used mathematical tool in agricultural system is bioeconomic modelling due to its ability to relate the biophysical and economic components of agricultural systems (Brown, 2000; Knowler, 2002; Llorente & Luna, 2016; Castro et al., 2018).

2.10.2. Bioeconomic Modelling in Agricultural Systems

Bioeconomic modelling refers to the development and application of models that integrate biophysical and economic components (Brown, 2000; Castro, 2018). The models are diverse ranging along a continuum from economic models with some biophysical variables to biophysical models with economic analysis (Brown, 2000). This flexibility and wide scope enables the use of bio-economic models to support either ex-ante or ex-post decisions on resources allocation, policies evaluation and technologies application at different levels along the agricultural system (Janssen et al., 2010; Flichman, 2011; Gowen & Bray, 2016). The biophysical component in agricultural system comprises the natural and biological processes which are dynamic, while the economic component describes the decision objectives on the economic implications of changes in the biophysical parameters (Flichman & Allen, 2013; Llorente, 2016). The dynamic nature of the biophysical component can be mimicked by simulation while identification of the best choices on decision objectives can be achieved through optimization modelling (Janssen, 2010). Deductively, bio-economic models can apply either or combine simulation and optimization modelling in a positive or normative approach resulting in models that range from static to complex mechanistic models (Appendix 1) (Brown, 2000; Flichman, 2013; Llorente, 2016; Castro, 2018).

2.10.3. Optimization modelling

Optimization programming can be categorised either as linear or nonlinear, continuous or discrete, deterministic or stochastic and static or dynamic based on the nature of the decision variables, constraints and modelling objective (Luenberger & Zhu, 2008; Lin et al., 2012; Lund et al., 2017). Linear programming assumes linearity among the decision variables and constraints while nonlinear programming accommodates non proportionality of the decision variables or constraints with the function objective (Luenberger, 2008). The use of either real or integer values for decision variable describes the programming method either as integer programming where variables assume numerals or mixed integer programming where both real and integer variables are used

(Lund, 2017). Optimization models in which decision variables are accurately known are termed deterministic, else stochastic if the variables are uncertain and probabilistic (Stygar, 2010; Lin, 2012). Unlike in static optimization where variables and constraints are constants over time, variables in dynamic programming are time dependent and therefore, decision making process is sequential and multistage (Stygar, 2010).

Optimization models can be used in agricultural system to determine the best outcome for a defined objective by considering the available limited resources and alternatives, subject to constraints (Wilton et al., 1974; Ridler et al., 2001; Stygar, 2010; Gouttenoire et al., 2011). The objective can be to identify an optimal solution in innovation assessments, policy analysis, research prioritization or evaluation of alternative agricultural management practices (Ridler, 2001; Gouttenoire, 2011; Doole et al., 2012; Bicknell et al., 2015). Innumerable authors have demonstrated the application of the various optimization programming approaches in livestock systems such as; to support decision making in enterprises planning, least cost ration formulation, feeding and breeding policy evaluation and technologies and innovations selection (Wilton, 1974; Glen, 1987; McCall et al., 1999; Doole, 2012; Segura et al., 2018). Although optimization programming can allow for determination of the best outcome for an objective, the approach does not show the system behaviour under varying conditions typical of agricultural system (Stygar, 2010). Hence, optimization approaches are often applicable where decision making requires optimal solution rather than where options produced by studying the interaction and relationships among system components are compared, which is the basis for simulation modelling (Stygar, 2010). Some potential applications of optimization modelling in the current study can include, determining the best combination of shrub species that can maximize fodder availability, land allocation to various farm enterprises including shrub to maximize farm income and evaluating seasonal pastures and shrubs feeding policy that can minimize fluctuations of seasonal feed availability. However, the paucity of data on the use of shrub in hill country farms and the need for highly accurate data to make meaningful conclusions in optimization modelling limits its application in this study.

2.10.4. Simulation modelling

Simulation modelling refers to the development of models that mimic the behaviour or processes of a real or proposed system for purposes of making observations to enable decision making about the system (Carter et al., 2020). The models can be descriptive, only describing the system behaviour, or explanatory factor, where in addition they define the mechanisms and processes that produce the behaviour in the system (Dent et al., 1979). Unlike optimization models, which can be inflexible and provide optimal solutions, simulation models are interactive, allowing for manipulation of variables and experimenting with events to provide options and solutions to what-if questions under varying conditions (Molnar, 2005; Woodward, 2008; Bicknell, 2015).

Some merits of simulation modelling include; time scaling of events, the ability to try and verify new designs, policies and processes without disturbing the real system and the repeatability and duplication in comparable systems (Dent, 1979; Carter, 2020). These merits makes simulation modelling useful in the study of systems that are complex, delicate or sensitive which can be too expensive, risky or infeasible to study (Molnar, 2005; Carter, 2020). As such, simulation models have vast applications from the cellular level to complex systems that integrate nested sub-systems in agricultural system (Dent, 1979; Molnar, 2005; Ahmed, 2020). This diversity of applications have produced numerous simulation approaches that range from single enterprise at farm level to composite farming systems at macro level (Peart & Curry, 1998; Bicknell, 2015). The farm level simulation models can focus on the performance of a single or multiple livestock or crop or mixed enterprises and their inter-relationships with biophysical, social and economic sub-systems and can be the basis for farm systems decision making and improvement (Black, 2014; Drinkwater, 2016). Some simulation approaches at macro level include agro-climatological, agro-ecological, socio-economic, and bio-economic modelling. Application of simulation modelling in the current study can include, mimicking native shrubs growth and fodder production, impact of native shrubs shading effects on pasture growth and yield, sheep flock performance with changes in farm feed supply, changes in farm cash flow with different native shrubs planting rates interventions.

2.10.5. Simulation Optimization modelling

An agricultural system is a composite of sub-systems, which in complex system modelling can cause multiple nonlinearities, combinatorial relationships and uncertainties, making either optimization or simulation modelling impractical (April et al., 2003). As such, a modelling approach that combines the optimization and simulation principles can be used to find solutions to complex systems that can be mathematically intractable (Fu, 2002; April, 2003). Hence, simulation optimization modelling seeks to find an option from numerous outputs of a simulation event that can lead to an optimal solution (April, 2003; Amaran et al., 2016). Optimization can be integrated in simulation models through four main approaches; stochastic approximation, sequential local response metamodels, random search and sample path optimization (Fu, 2002). Since this modelling approach is mainly applicable in complex systems, this limits its use in the current study.

Identified gaps on the use of New Zealand native shrubs on hill country sheep and beef farms.

The following are some of the gaps identified during the literature review.

1. New Zealand has a vast native shrubs resource that are consumed by wild herbivores but their use to feed farmed ruminants have not been explored.
2. There are limited studies examining native shrubs intake and preference by farmed ruminants.
3. The nutritional composition of the browsable native shrubs have only been scantly evaluated.
4. Non-nutritive compounds present in native shrubs that can be beneficial or detrimental to browsing animals have not been evaluated.
5. Rumen fermentation characteristics of browsable native shrubs have not been evaluated.
6. The biomass and carbon stock properties of native shrubs has only been scantly estimated.
7. The farm economics of using native shrubs on hill country sheep and beef farms have not been widely studied.
8. There is no published simulation modelling studies involving the use of browsable native shrubs on hill country farms.

Chapter 3: Bioeconomic Modelling to Assess the Impacts of Using Native Shrubs on the Marginal Portions of the Sheep and Beef Hill Country Farms in New Zealand

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Abstract

New Zealand hill country sheep and beef farms contain land of various slope classes. The steepest slopes have the lowest pasture productivity and livestock carrying capacity and are the most vulnerable to soil mass movement. A potential management option for these areas of a farm is the planting of native shrubs which are browsable and provide erosion control, biodiversity, and a possible source of carbon credits. A bioeconomic whole farm model was developed by adding a native shrub sub-model to an existing hill country sheep and beef enterprise model to assess the impacts on feed supply, flock dynamics, and farm economics of converting 10% (56.4 hectares) of the entire farm, focusing on the steep slope areas, to native shrubs over a 50-year period. Two native shrub planting rates of 10% and 20% per year of the allocated area were compared to the status quo of no (0%) native shrub plantings. Mean annual feed supply dropped by 6.6% and 7.1% causing a reduction in flock size by 10.9% and 11.6% for the 10% and 20% planting rates, respectively, relative to 0% native shrub over the 50 years. Native shrub expenses exceeded carbon income for both planting rates and, together with reduced income from sheep flock, resulted in lower mean annual discounted total sheep enterprise cash operating surplus for the 10% (New Zealand Dollar (NZ$) 20,522) and 20% (NZ$ 19,532) planting scenarios compared to 0% native shrubs (NZ$ 22,270). All planting scenarios had positive Net Present Value (NPV) and was highest for the 0% native shrubs compared to the 10 and 20% planting rates. Break-even carbon price was higher than the modelled carbon price (NZ$ 32/ New Zealand Emission Unit (NZU)) for both planting rates. Combined, these results indicate planting native shrubs on 10% of the farm at the modelled planting rates and carbon price would result in a reduction in farm sheep enterprise income compared to the status quo without native shrubs planted. It can be concluded from the study that a higher carbon price above the break-even can make native shrubs attractive in the farming system.

Keywords: Bioeconomic modelling; native shrubs; cash operating surplus; hill country sheep and beef

3.1. Introduction

Sheep and beef cattle in New Zealand are managed together to complement pasture utilization (Morris, 2014) and they contribute more than 95% of the red meat produced that is available for export (Beef+Lamb NZ, 2020c). In 2020, there were approximately 26 million sheep and 3.89 million beef cattle in New Zealand (StatsNZ, 2020; Beef+lamb NZ, 2022). Sheep and beef cattle farms occupy approximately 63% of agricultural land with over half of the farms located on hill country (Beef+Lamb NZ, 2020b).

Hill country is classified as land below 1,000 m asl (above sea level) containing slopes greater than 15° and account for approximately 37% of the farmed land in New Zealand (Kemp, 2016). The slopes across hill country farms differ, but are generally a mixture of low (<7°), medium (8 to 20°) and steep (>21°) slope classes (Hodgson et al., 2005; Beef+Lamb NZ, 2020c). Land use and productivity varies with slope; low and medium slopes are mainly planted with improved pastures, while less grazable steep slopes may be used for grazing or utilized for plantation forestry with the non-utilisable portions allowed to revert to native vegetation (Morris, 2014; Basher, 2016; Beef+Lamb NZ, 2020c). Even with improved pastures, low herbage production on the steep slopes limits their use for grazing, often with a carrying capacity of less than eight stock units per hectare (Praat, 2011; Lambert et al., 2014; Kemp, 2016).

Native vegetation on hill country sheep and beef farms currently represents approximately 12% of the national native vegetation cover (Norton, 2018; Beef+Lamb NZ, 2020b), indicating the contribution these farm types are making to revegetation and restoration of native flora. The historically low native vegetation cover occurred from clearance for pasture expansion in the early 1900s, which exposed some hill country to the vulnerability of soil mass movement, environmental degradation, and loss of native biodiversity (Kemp, 2016). Attempts to mitigate soil mass movement in hill country have mainly utilized spaced exotic species such as poplars (*Populus* spp) and willows (*Salix* spp) (Eyles, 2010) and land use change to plantation forestry with radiata pine (*Pinus radiata*) (Basher, 2013). Poplars and willows are comparatively easy to establish, have deep and expansive roots that stabilize steep slopes (Eyles, 2010; McIvor, 2012; Basher, 2013), can supply valuable fodder (Kemp, 2003; Jones, 2013) and if well-spaced can provide carbon trade income (McIvor, 2012; Ministry for Primary Industries, 2017), but they are deciduous and management intensive (McIvor, 2006). Plantation forestry can provide erosion control and income from carbon trade and sale of logs (Eastland Wood Council, 2009), but their monoculture limits biodiversity, understory grazing, and can result in accelerated erosion during and after harvesting if not replanted (Basher, 2016).

An alternative to exotic species is the use of native trees and shrubs which are endemic and adaptable to New Zealand conditions (Norton, 2018). Additionally, native plants are culturally valued, can enhance biodiversity restoration, control erosion, improve landscape aesthetics, provide income from carbon trade, and can be a potential source of fodder to livestock (Dodd, 2007; Beets, 2014b; Kimberley, 2014; Norton, 2018). However, knowledge on the management of cultivated native shrubs in New Zealand and their role in erosion control, fodder production and their nutritive value for livestock, and the economics of establishing them on hill country sheep and beef farms is lacking (Dodd, 2007; Beef+Lamb NZ, 2018b). Bioeconomic modelling of establishing native shrubs on hill country sheep and beef farms using the limited literature data available can provide some of these insights.

Hill country sheep and beef farms are complex and dynamic systems consisting of biophysical, social and economic components, which interact and influence farm sustainability and profitability (Bryant & Snow, 2008; Farrell, 2020). Models integrating both biophysical and economic components, commonly referred to as bioeconomic models, are more robust in evaluating impacts of changing farming practices or applying a new intervention (Bryant, 2008). A bioeconomic model for North Island hill country sheep and beef farm was developed by Farrell (2020) and used to examine the impacts on farm productivity and profitability of various changes in the sheep and beef cattle management on these farms (Farrell et al., 2019, 2020b, 2021a, 2021b). However, like many models used for hill country sheep and beef farm systems (Bicknell, 2015; Hendy et al., 2019), the model did not consider native shrubs as part of economic land use. Therefore, the objective of this study was to develop a native shrub sub-model to add to the existing model developed by Farrell (2020) and thereafter use it to assess the impacts on; (i) farm feed supply, (ii) flock dynamics and (iii) farm economics of converting 10% of a North Island hill country sheep and beef farm from pasture to native shrubs with understorey grazing.

3.2. Methods

3.2.1. Model development and structure

A bioeconomic whole-farm system dynamics model was developed in STELLA Architect version 1.9.3 (version 2019), to represent a North Island hill country sheep and beef enterprise in New Zealand based on the model of (Farrell, 2020). The model assessed changes in feed, sheep numbers, and cash flow dynamics for 50 years with and without a portion of the farm (up to 10%) planted in native shrubs at two planting rates (10 and 20%). The model combined the established hill country sheep and beef enterprise model (HCM) utilized by (Farrell, 2019; Farrell et al., 2020a; Farrell, 2021a) with a new native shrub sub-model (NSM) and was structured into modules representing biophysical and economic sub-systems and their interactions (Figure 1). Details on the dynamics of the HCM are outlined in (Farrell, 2019).

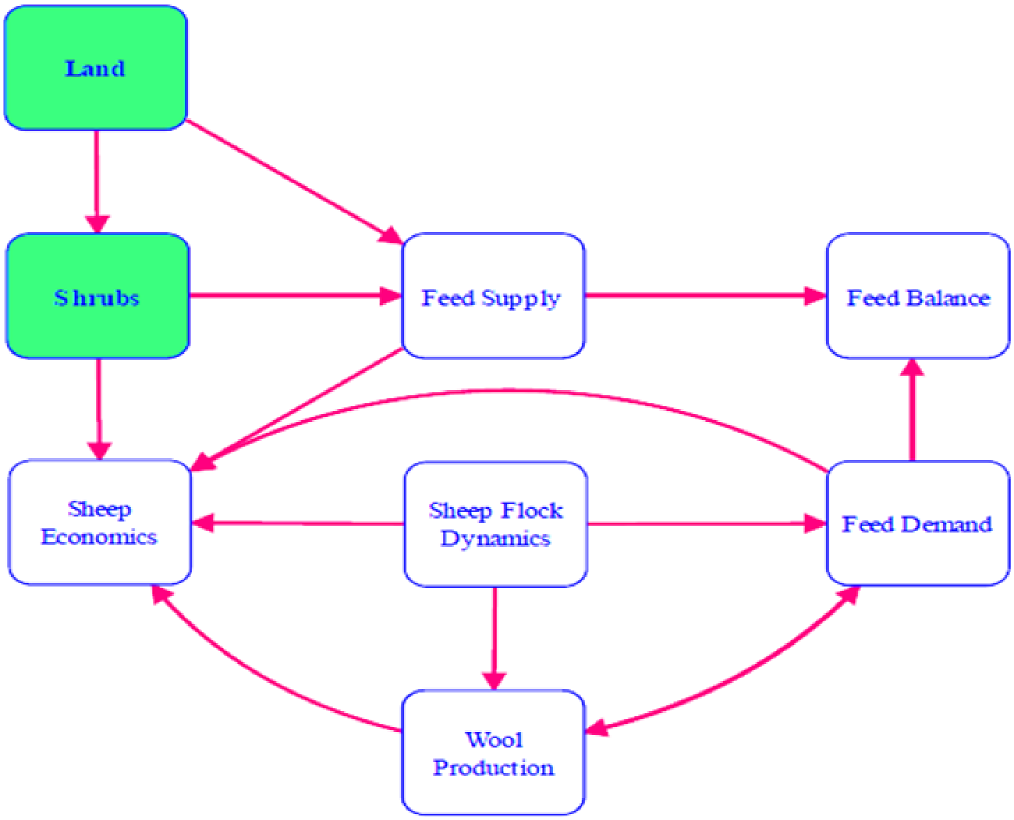

Figure 15. A simplified diagram of the North Island hill country sheep and beef whole farm system dynamic model comprising modules of hill country sheep enterprise (HCM) (white fill based on Farrell et al. (2019)) and new native shrub (NSM) models (green fill). The arrows indicate the direction of interaction among the modules.

The established HCM model (Farrell, 2020) assumed that hill country terrain was constant across the entire farm, and therefore, the pasture yield and quality per hectare were uniform. Further, pastures supplied all the flock feed needs and that the sheep and beef enterprises were the only source of farm cash flow (Farrell, 2020). However, hill country farms are characterised by a mixture of slopes, which can influence pasture production and quality and thus affecting farm animal carrying capacity and cash flow (López, 2003; Kemp, 2016). Moreover, hill country sheep and beef farms often use supplementary feeds such as conserved pasture, crops, grains and tree and native shrub herbage during seasons of low feed quantity and energy supply (Morris, 2014). In addition, hill country farms can have diverse income including sale of logs (Bay of Plenty Regional Council, 2020) and the carbon credit (Dodd, 2007; Moot, 2009). Therefore, a new NSM sub-model was developed to allow; (i) partitioning of hill country farm into various slope classes that vary in pasture growth and quality, (ii) use of native shrubs as an additional feed source, (iii) diversification of land uses to encompass native shrub land and (iv) expansion of sources of farm income to include carbon emission trading.

3.2.2. Land characteristics for modelled farm

In New Zealand, North Island hill country sheep and beef farms can be sub-divided into hard-hill and hill country based on slopes and land use capability (Campbell, 1973). The hard-hill country farms are predominantly steep with characteristically low soil fertility and a carrying capacity of less than 10 stock units per hectare (SU/ha, 1 SU equals the annual feed requirement of a 55 kg ewe rearing 1 lamb to weaning at 28 kg), whereas hill country farms have relatively less steep topography with greater soil fertility and therefore a higher livestock carrying capacity of up to 13 SU/ha (Campbell, 1973; Beef+Lamb NZ, 2020a). Hill country farms contain a mixture of slopes (Lynn, 2009) that can be grouped broadly into; low (flat), medium (rolling) and steep slope classes (Praat, 2011; Basher, 2013; Saggar, 2015). The blend of slopes varies across farms and regions resulting in disparities among studies on slope classes (Table 5) and their proportion on a hill country farm (Table 6). Therefore for the current model, a typical farm with a productive land area of approximately 564 ha in the East Coast region of New Zealand (Beef+Lamb NZ, 2020a) was used as the archetype for the North Island Hill country farm. Sheep and beef cattle farms in the East Coast region can be grouped into hard hill (class 3) and hill country (class 4) farms based on land usability (Lynn, 2009; Beef+Lamb NZ, 2020a). The East Coast region of New Zealand was chosen due to the dominance of hill country terrains (Saggar, 2015; Lambie, 2018; Spiekermann & Marden, 2018). The region also accounts for approximately 50% of the North Island sheep population (Beef+lamb NZ, 2022) and was the base region for the HCM (Farrell, 2019).

Table 5. Published classifications of North Island sheep and beef hill country farm slopes based on slope classes (low, medium and steep).

Slope elevation (°)			Author (s)
Low	Medium	Steep	
<7	8 to 20	>21	(Beef+Lamb NZ, 2020b)
<15	16 to 20	>21	(Hodgson, 2005)
<12	12 to 24	>24	(Basher, 2013; Saggar, 2015)
1 to 12	13 to 25	>26	(Lambert, 1983, 2014; López, 2003; Hedley et al., 2015; Kemp, 2016)
0 to 10	10 to 24	25 to 37	(Ledgard et al., 1982)
<15	15 to 25	>25	(Praat, 2011)
0 to 15	16 to 25	>26	(Page, 1988; Harmsworth, 1996; Lynn, 2009; Hedley, 2015)
0 to 15	16 to 25	>26	(Murray et al., 1999)

Table 6. Published proportions of the three slope classes (low, medium and steep) as percentage of the total hill country farm studied in New Zealand.

Slope class proportion (%)			Scope of the study	Author
Low	Medium	Steep		
11.0	32.0	40.0	New Zealand	(Beef+Lamb NZ, 2020b)
19.6	34.5	45.9	New Zealand	(Saggar, 2015)
55.0	13.0	35.0	New Zealand	(Hodgson, 2005)
30.1	12.8	57.1	North Island	(Page, 1988)
10.0	18.0	60.0, 12.0 [1]	East Coast (Gisborne)	(Murray, 1999)
8.7	45.9	45.5	East Coast	(Saggar, 2015)
14.5	57.9	27.6	Northland-Waikato-Bay of Plenty	(Saggar, 2015)
11.2	27.7	61.1	Taranaki-Manawatu	(Saggar, 2015)
15.6	15.8	68.5	Marlborough-Canterbury	(Saggar, 2015)
36.6	29.7	33.7	Otago-Southland	(Saggar, 2015)
14.1	15	70.9	Wairarapa	(Cameron, 2016)

[1] Proportion of hill country classified as extreme slope (near vertical)

Based on published data, the slope types of the modelled North Island hill country sheep and beef farm were grouped into; low (<12°), medium (13 to 25°) and steep (>25°) slope classes (López, 2003; Hedley, 2015) to capture the critical slopes relevant to pastoral land use (Lynn, 2009) and pasture production (Burggraaf, 2018). Slope classes were apportioned as 8.7%, 45.9% and 45.4% for low, medium, and steep slope classes, respectively, and were used to reflect the average slope mix of East Coast hill country farms (Saggar, 2015, Table 2). The model assumed that approximately 10% (56.4 ha) of the total effective farm area would be used for planting native shrubs. This area was assumed to be taken from the steep slope (>20°) portion of the farm, due to its low carrying capacity (herbage production) and vulnerability to erosion (Marden, 2018a).

3.2.3. Modelled native shrubs planting on hill country farm.

Two annual native shrub planting rates of 10% and 20% were applied to mimic the likely land use change scenarios that could occur with establishment of native shrubs. The native shrub planting rates determined the proportion of the area set aside (56.4 ha) for planting native shrubs that was planted annually. The 10% planting rate assumed that the area set aside for planting native shrubs was divided into ten portions that were planted consecutively for ten years. Similarly, the planting rate of 20% assumed the area was divided into five equal portions which were planted over five consecutive years. When no native shrubs were planted, a 0% native shrub planting rate was used in the model.

3.2.4. Sheep flock structure and dynamics

The sheep flock and beef herd classes and structure used in the HCM (Farrell, 2019) were retained in the current model. Beef herd size was held constant in both the base and current model and only the sheep flock size was affected by land use change from pasture to native shrubs on the steep slope portions of land. The holding of the beef herd data constant has been utilized in previously in HCM model studies (Farrell, 2019, 2020b; Farrell et al., 2020d; Farrell, 2021b, 2021a, 2020). In the current model, sheep flock size was adjusted to values reported for sheep and beef hill country farm (class 4) in the East Coast region of the North Island for the production year 2018/2019 (Beef+Lamb NZ, 2020a).

The sheep flock in both the current and the base model was self-replacing with no external sourcing of replacement flock (Farrell, 2019). Flock dynamics in the base model was based on a constant feed supply and thus flock replacement rates (R) were determined by ewe culling rates (C) and deaths (D) for all age groups (i) at a given time (t) (Farrell, 2019). In the current model, feed supply varied among native shrubs planting scenarios resulting in fluctuating feed balance which affected the flock dynamics. Feed balance (F) was therefore, used in addition to ewe culls and deaths to determine flock replacement rates in the current model. It is estimated that a mature ewe requires approximately 6,600 megajoules of metabolizable energy (MJ ME) annually (Nicol &

Brookes, 2017; Webby & Bywater, 2017) and this value was used to determine ewe number changes with fluctuations in feed balance with conversion of pasture to native shrubs (i.e. up to 10% of total farm area over time). The lamb flock size in both the current and base models was dependent on farm feed supply (Beef+Lamb NZ, 2012; Farrell, 2020) and the lamb selling policy in the HCM model was retained.

Equation 1
$$R_t = \sum_{i=1}^{I}\big((D_i + C_i) + (\mathrm{int}\,(F_t/6600))\big),$$
$$\text{If}, -6600 > F_t > 6600 \text{ then } F_t = 0$$

3.2.5. Pasture growth on hill country farms

Pasture production on hill country sheep and beef farms is influenced by the slope and aspect, which modifies the microclimate and soil properties of the terrain (López, 2003; Kemp, 2016) as shown in (Table 7). Monthly pasture growth rate estimates for the region for this farm class were used as the average for the low slope class (Trafford & Trafford, 2011). The percentage difference in pasture production on the medium and steep slopes, relative to low slope, were based on (Kemp, 2016). The pasture production was adjusted to ensure the medium and steep slopes pasture production was 52.1 and 38.1% of the flat slope, respectively. This enable the modelled farm to support flock numbers similar to those for a class 4 hill country farm on the East Coast region of New Zealand (Beef+Lamb NZ, 2020a)

Table 7. Published percentage of pasture production on medium and steep slopes relative to the low slope and the estimated pasture yields from the three slope classes (low, medium, and steep) on New Zealand North Island sheep and beef hill country farms.

Pasture % change relative to the low slope			Pasture yield (DM kg/ha/y)			Source
Low	Medium	Steep	Low	Medium	Steep	
100	46.2	31.9	12,568	5,806	4,003	(Kemp, 2016) [1]
100	73.8	65.6	13,803	10,188	9,050	(Lambert, 2014) [2]
100	81.6	61.3	15,773	12,878	9,669	(Lambert, 2014) [2]
100	77.2	58.0	14,072	10,857	8,164	(Lambert, 1983) [2]
100	76.9	46.2	9,425	7,250	4,350	(Praat, 2011) [3]

[1] Studies based on general southern North Island; [2] on summer moist and, [3] on Northland, sheep and beef hill country farms in New Zealand North Island.

3.2.6. Native shrubs growth and herbage yields

Several mathematical functions (linear, exponential, logarithmic, logistic and Gompertz) can be used to estimate growth in native shrubs but they differ in parameters utilized and growth curve characteristics (Paine et al., 2012). Linear regression functions have a constant growth rate, while exponential and logarithmic functions assume constant increasing and decreasing rate of growth, respectively (Paine, 2012). The constant rate of change in linear regressions limits their use in lifespan simulations since plant growth is affected by environmental factors and physiological stages (Paine, 2012). Logistic functions have a limitation to a radial symmetry on its curve, while Gompertz function curves are asymmetrical and thus most suitable for plant growth simulations (Paine, 2012; Cao et al., 2019).

A Gompertz function (Equation 2) was derived using *Eucalyptus saligna* (Eucalyptus) Nelder spacing data (McKenzie & Hay, 1996) due to unavailability of New Zealand native shrub data. The Gompertz function was based on trees planted at a density of approximately 1,000 stems per hectare (sph) and was used to simulate individual stem basal diameter (BD) growth (cm) for 50 years (t). A planting density of approximately 1,000 sph was used for the native shrubs since it was the common planting density used with exotic trees for erosion control on the North Island hill country farms. The tree planting density used achieves canopy closure relatively quickly, thus limiting weed encroachment (Dodd, 2007; Basher, 2016). In addition, the canopy cover meets the requirements of 30% for carbon trading registration in New Zealand (Ministry for Primary Industries, 2017).

Equation 2 $$BD = 26.221 \exp\left(-\exp\left(0.203\left(t - 5.751\right)\right)\right)$$

The estimated BD was used as an allometry in a power function to predict the herbage yield (HY) in kilogram of dry matter per tree (Equation 3) and was assumed to consist of leaves and edible stems not exceeding 5 mm in diameter (Oppong, 2001; Kemp, 2003).

Equation 3 $$HY = 0.0284BD^{2.113}$$

However, eucalyptus differ in physiognomy and have faster growth rates translating to higher biomass accumulation compared to native shrubs (Ministry for Primary Industries, 2017). Biomass accumulation is species specific, finite per unit area and can be used to estimate optimal foliage biomass for a given species (Ministry for Primary Industries, 2017; Ma, 2018). Native shrub foliage biomass was assumed to be 6.4% of the total carbon stock (Marden, 2005b, 2018b; Poorter, 2012a; Mason, 2014) and was predicted using the indigenous forest carbon stock per hectare for forests planted after 1990 (Ministry for Primary Industries, 2017). Therefore, a feedback loop relating BD and

HY to native shrub foliage biomass was used in the model to adjust the eucalyptus basal diameter growth to that expected for New Zealand native shrubs. The feedback loop delayed BD growth when HY exceeded the native shrub foliage biomass. The total native shrub herbage production of the farm was a function of the estimated HY, planting density, and the total area annually planted in native shrubs.

3.2.7. Native shrub understory pasture production

As the native shrub canopy expands with growth it reduces understorey pasture production by limiting water and photosynthetic light from reaching the ground (Benavides et al., 2009; Devkota et al., 2009). The rate of understory pasture reduction is dependent on canopy cover and is commensurate with the density per unit area of canopy providing plants (McElwee & Knowles, 2000; Devkota, 2009). In the model, the area planted in native shrubs was assumed to consist of both areas under and outside the canopy and therefore differed in pasture production due to canopy cover effects. Individual native shrub canopy was assumed to have a cylindrical base (Hussain, 2009) and the canopy diameter (CD) in meters was used to estimate the canopy area (CA) in meters squared (Equation 5). A linear allometric function (Scanlan et al., 2010, Equation 4) relating CD to stem basal diameter was used to determine the CD increase with native shrub growth. Total CA at a given moment on the area planted in native shrubs was obtained as a function of CA and native shrub density. Canopy cover was estimated using the total canopy area as a percentage of the total area planted in native shrubs. An exponential function (Equation 6) with an extinction point at 65% canopy cover was used to estimate understorey pasture reduction (PR) as a percentage relative to the open pastures (McElwee, 2000; Benavides, 2009).

Equation 4 $$CD = 1.966 + 0.115\mathrm{BD}$$

Equation 5 $$CA = \pi\ (0.5\ x\ CD)^2$$

Equation 6 $$PR = 99.979\ exp(-0.01CA)$$

The areas not under canopy were assumed to have pasture production like the steep slope class open pastures. Therefore, total pasture production from the area in native shrubs comprised of the understorey pasture and pasture from areas not under canopy.

3.2.8. Native shrubs carbon stock

Precalculated values of carbon stock per hectare for indigenous forest planted after 1990 were used as the annual carbon stock values for native shrub planted on the modelled farm (Ministry for Primary Industries, 2017). The net annual carbon stock accumulation was obtained as the difference between the current and the preceding year. In the model, the age of the native shrubs and annual total area in native shrubs were used to factor the total net carbon stock accumulation (Ministry for Primary Industries, 2017).

3.2.9. Farm feed supply, demand, and balance.

The total feed supply in mega joule of metabolizable energy (MJ ME) on the modelled farm comprised open pastures and native shrub forage. Open pastures were from the low and medium slopes and the portion of the steep slope without native shrubs while native shrub forage included pastures and native shrub fodder from the steep slope portion with native shrubs. Open pastures were available for grazing throughout the year for the modelled period. However, native shrub forage was only available five years after planting for each respective native shrub portion of land and could only be utilized for further five years (browsing window). The five-year period between planting native shrubs and the browsing window in each respective native shrub portion of land was assumed to allow the native shrubs to establish and avoid animal induced damage. Further, after the five-year browsing window (10 years after planting for each portion), the native shrubs were assumed to have a canopy cover above 65%, which restricted understory pasture growth.

Pasture utilization by sheep was assumed to be approximately 70%, typical of North Island sheep and beef hill country farms (Webby, 2017; Farrell, 2020). Similarly, a 70% utilization rate was assumed for the accessible native shrubs fodder due to unavailability of native shrub utilization data for New Zealand. However, native shrub height *(H)* increase with age was assumed to affect fodder available to sheep. Native shrub height increase in meters with time was predicted with a power function allometry (Equation 7) using native shrub BD. Sheep can reach to browse heights of 1.17 m (Sanon et al., 2007; McEvoy & McAdam, 2008) with increasing heights reducing the accessible browse. In the model, sheep browsed the native shrubs fully to a height of 0.87 (Sanon, 2007) after which available browse *(AB)* reduced logarithmically (Equation 8) to no access when the total native shrub height reached 5.0 m. At the total native shrub height of 5 m, the accessible edible foliage below 1.17 m was assumed to be limited due to self-pruning of lower branches due to shading effect from canopy closure (Mäkelä, 1997).

Equation 7 $$H = 0.1976BD^{1.1436}$$

Equation 8 $$AB = -0.516\, ln(H) + 0.8839,$$

where, AB= 1 if H<0.87 and AB=0 if H>5

Annual feed demand was estimated using approximations of feed requirements for each sheep class (Farrell, 2019) and the difference with feed supply was taken as the farm feed balance. The beef cattle herd was held constant and thus beef cattle feed demand in both the base model and the current model were constant over the modelled period. The approach of holding the beef feed demand constant has been used previously with the bioeconomic model (Farrell, 2019; Farrell et al., 2020e; Farrell, 2021a, 2020).

3.2.10. Farm economics

The steep slope portion on hill country sheep and beef farms are commonly grazed by sheep and converting part of this portion of land to native shrub was assumed to affect the sheep carrying capacity rather than the beef herd. Hence, the beef enterprise income and costs on per hectare basis were assumed to be unaffected in the economic assessment, which included discounted net cash flow in terms of cash operating surplus (COS), net present value (NPV), internal rate of return (IRR) and break-even analysis. Two native shrub planting rates (10% and 20%) were compared to a base scenario without native shrubs (0% native shrubs) at three discount rates (5%, 7% and 10%) for 50 years. The COS for the sheep enterprise and sheep enterprise with native shrub was obtained as the difference between cash income and cash operating expenses. Sheep enterprise COS estimation followed the previously used (Farrell, 2019) approach, while native shrub enterprise COS was derived using cash inflow from carbon trade and cash outflow from expenses associated with pre-planting, planting and post planting expenses. The current two-year average of NZ$ 32/NZU (NZU, New Zealand Emission Unit) (Mathilde, 2021) was used as the carbon price in the current model. The NPV (Equation 9) was used to assess the total value of planting native shrubs at the two planting rates vis a vis not planting.

Equation 9 $$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+\rho)^t}$$

Where, R is net cash flow in New Zealand dollars (NZ$) at time t, ρ was the discounting rate and n = 50 is the investment duration

Annual IRR for planting native shrubs at different rates was estimated by determining the discounting rate at which NPV was equivalent to zero. A break-even analysis was also undertaken to estimate the carbon price at which the NPV for the native shrub inclusive model equalled the base (no native shrub) model.

3.3. Results and Discussion

The results comparing the impacts of up to 10% of the modelled farm in native shrubs on farm feed supply, sheep flock dynamics and farm economics are discussed in the following sections.

3.3.1. Farm feed supply

Figure 16 shows the annual feed supply for annual shrub planting rates of 0% (base model), 10% and 20% per year over 10% of the farm for 50 years. Annual feed supply in MJ ME remained constant for 0% native shrubs but had a staggered decrease in the 10% and 20% native shrub planting rates before levelling off after 16 and 14 years, respectively. The initial decrease was highest in the 20% planting rate due to the greater areas being removed per year from grazing. The long-term reduction in annual feed supply for both planting regimes (21.46 million MJ ME) compared to the base model (23.23 million MJ ME) was 7.6%. The long-term feed supply reduction was the same for both planting rates due to the consistent 10% reduction in grazing area, post the transition periods, and resulted in lower but varying mean annual feed supply for the planting rates regimes relative to base model.

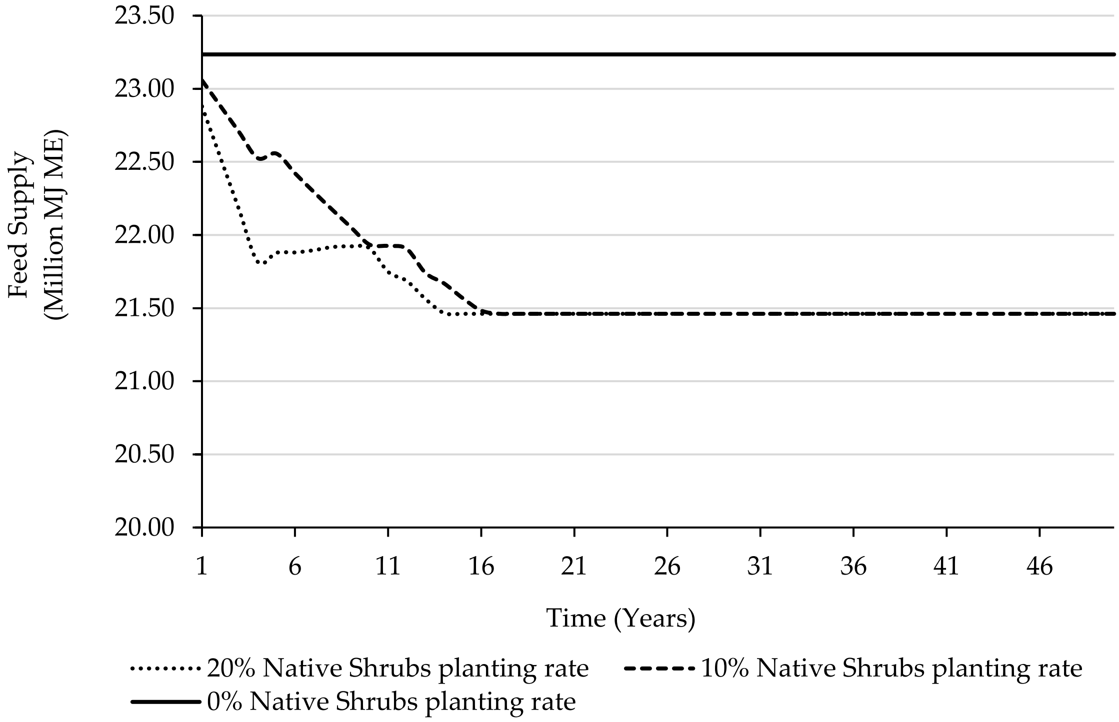

Figure 16. Annual feed supply for 50 years in metabolizable energy (million mega joules) with native shrubs planted on 10% of the modelled farm at three planting rates (0%, 10% and 20% per year).

The lower mean annual feed supply for the 10% and 20% planting rates, compared to the 0% rate was due to a reduction in pasture production area on the steep slopes and the restricted period of browsing for the shrubs between years 5 and 10 post planting. However, the mean reduced annual feed supply overall, for the 10% and 20% planting rates, compared to the base model (Table 8), was proportionately less than might be expected. This can be attributed to the low pasture production on steep slopes compared to the easier slopes (Praat, 2011; Lambert, 2014; Kemp, 2016).

Table 8. Total mean farm annual feed supply in metabolizable energy (million mega joules) for the modelled farm based on low, medium and steep slope types with shrubs planted on 10% of the farm on the at three planting rates (0%, 10% and 20%) per year, and corresponding mean annual feed allocation to sheep and beef cattle.

Planting Rate (%)	Slope categories mean annual feed supply			Farm mean annual feed supply	Feed supply to sheep		Feed supply to beef	
	Low	Medium	Steep		Feed	%	Feed	%
0	4.05	11.13	8.05	23.23	13.94	60.0	9.29	40.0
10	4.05	11.13	6.51	21.69	12.40	57.2	9.29	42.8
20	4.05	11.13	6.41	21.59	12.30	57.0	9.29	43.0

Comparatively, the mean annual feed supply for the base model when converted from MJ ME to dry matter kilograms per hectare (DM kg/ha/y) for the low (11,700 DM kg/ha/y), medium (6,140 DM kg/ha/y) and steep slope (4,490 DM kg/ha/y) was within the ranges reported for North Island hill country sheep and beef cattle farms in New Zealand (Lambert, 1983, 2014; Praat, 2011; Kemp, 2016). This indicates the model adequately represented the current state of the North Island hill country sheep and beef cattle farms feed supply, before the introduction of native shrubs on portions of the steep slopes.

Beef cattle were allocated a constant feed supply of the modelled total mean annual farm feed supply, with the remainder utilized by sheep. The reduction in annual mean farm feed supply with conversion of pastures to native shrubs resulted in a greater proportion of feed allocated to beef cattle for the planting rates compared to the 0% native shrubs, to maintain a constant feed supply to the beef cattle herd. The fluctuations in the feed supply proportions for the beef cattle herd and sheep flock are common in hill country sheep and beef cattle farms with adjustment of the farm stock sizes to meet the feed supply (Beef+Lamb NZ, 2018a; Farrell, 2020b, 2021b). Feed supply for the beef cattle was from the open pastures and only sheep browsed the native shrub areas due to the potential for cattle to excessively damage the shrubs. The bulk of the shrub area forage was from understory pasture rather than the shrub fodder (Figure 17). Accessible fodder was assumed to be directly harvested by sheep, whereas with mature willows and poplar fodder is available only after pollarding or coppicing (Kemp, 2001, 2003). The low feed supply from shrub fodder and changes over time can be attributed to reduced access as the shrubs increased in height (Brookshire et al., 2002; Ouédraogo-Koné et al., 2006; Sanon, 2007).

Mean pasture feed supply on slopes planted with shrub was higher for the 10% planting rate than the 20% planting rate but mean shrub fodder was not greatly affected by shrub planting rate (Figure 17). The higher mean pasture feed supply for the 10% native shrub planting rate compared to the 20% planting rate, resulted from less land converted annually to native shrubs and therefore sheep had longer cumulative feed supply from open and understorey pastures compared to the 20% planting rate on the shrub area. The similar native mean shrub fodder over the 50 years for the 10% and 20% native shrub planting rates, can be explained by the fact that an equal number of native shrubs were planted over time (1,000 stems per hectare), for each planting rate on a cumulatively equal portion of the steep slope (up to 10% of the modelled farm) and were browsed for a similar duration (five years).

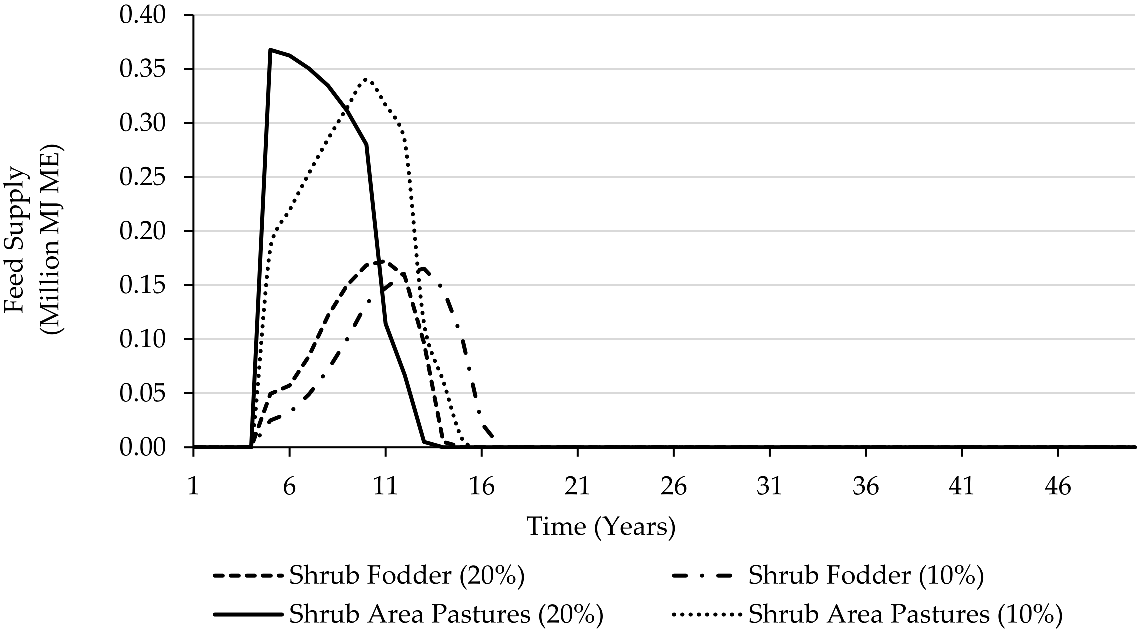

Figure 17. Total shrub forage (shrub fodder, understory, and open pastures) in metabolizable energy (million mega joules) per year for 50 years, on 10% of the modelled farm planted in native shrubs at 10% and 20% per year planting rates.

3.3.2. Flock dynamics

Flock size differed (Figure 18) with changes in feed supply with different native shrub planting rates. Mean annual flock size remained uniform at 2,747 sheep over the modelled period for the base model (0% native shrub) but reduced by 10.9% and 11.6% (mean) for the 10% and 20% planting rates, respectively. The decrease in flock size for these scenarios was achieved by reducing the number of replacement ewe lambs entering the flock and therefore selling more lambs, rather than culling the ewe flock. Reducing flock size by preference of culling older ewes has been shown to reduce flock meat production and ewe reproductive performance, which peaks at five years of age (Farrell, 2019, 2020b). Therefore, it was decided to avoid these potential negative effects.

In scenarios with planting of native shrubs there was a decrease in flock size for initial five years that was followed by flock size fluctuations for both the planting rates. The initial constant decrease in flock size was due to decrease in feed supply from land being withdrawn from grazing without compensatory feed supply, while the fluctuations resulted from the sequential opening and closure of the browsing window for the consecutive portions planted in native shrubs. Overall flock size on the modelled farm stabilized after 17 and 15 years for the 10% and 20% planting rates, respectively, across the 50 years modelled. This corresponded to 7 and 10 years after the last planting for the 10% and 20% planting rates, respectively. The long flock stabilization period for the 20% planting rate compared to 10% was due to a greater total feed decrease and thus lower replacement ewe lambs retained during the native shrubs establishment period (10 and 5 years for 10% and 20% planting rates, respectively). Low replacement ewe lamb rates resulted in a gradual transient decrease in ewe flock size along the ewe flock age classes affecting the long term flock reproductive performance (Farrell, 2019, 2020b), combining to produce prolonged flock size fluctuations. However, the long flock stabilization periods are unlikely to be experienced on most farms, because flock size management is typically based on short-term forecasted feed supply (Beef+Lamb NZ, 2018a) whereas in the model current annual feed supply determined flock size.

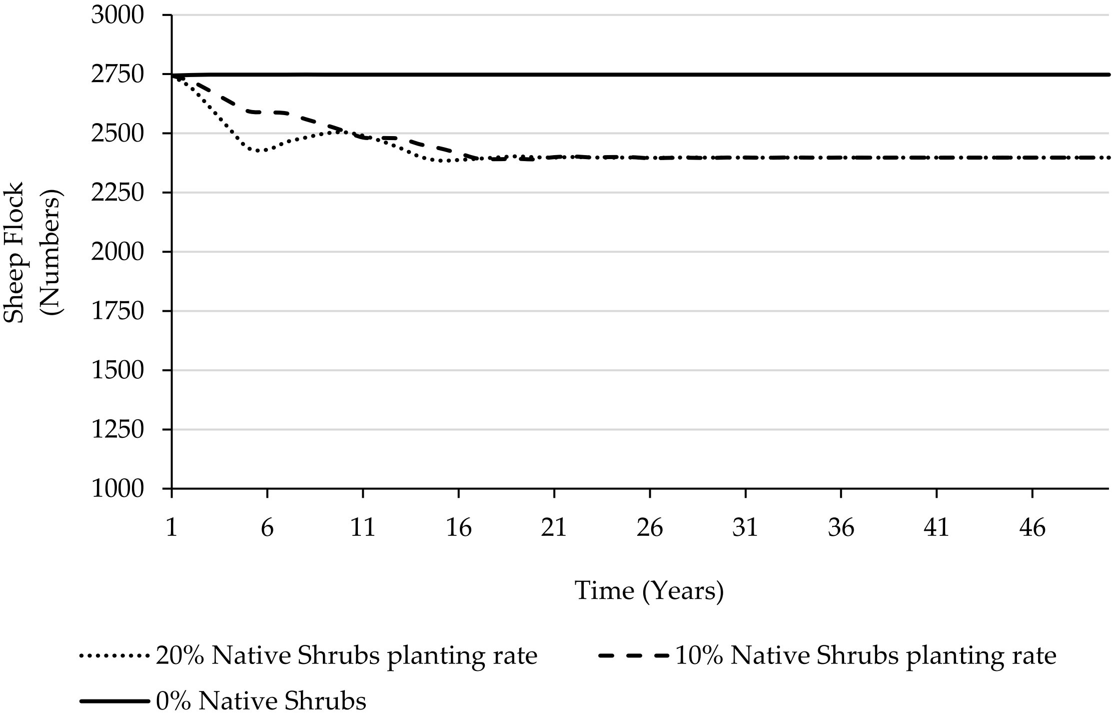

Figure 18. Fluctuation in sheep flock size with native shrubs planted on 10% of the modelled farm at 0%, 10% and 20% planting rates per year, over 50 years.

The overall flock structure, across time, was similar in all native shrub planting rates and comprised of 78.7% mixed age ewes, 20.0% replacement ewe lambs and 1.3% other sheep. The flock structure for the modelled farm was similar to the average sheep flock structure on the North Island sheep and beef farms (Beef+Lamb NZ, 2020a). The consistency in flock structure over the modelled period and scenarios, indicates that the model regulated flock dynamics based on the modelled farm annual feed supply.

3.3.3. Farm economic analysis of establishing native shrub

Economic analyses in agricultural enterprises provide means for choosing among alternative investment opportunities based on their broad sustainability and projected financial viability (Hopkinson, 2017). Sheep and beef cattle are the major enterprises in the New Zealand hill country sheep and beef cattle farms and their economic worth have been widely studied (Evison, 2008; Beef+Lamb NZ, 2017, 2020b; Farrell, 2021a). However, native shrubs are gaining interest as alternative complementary investment on hill country sheep and beef cattle farms but their economic value within the farm system is currently anecdotal (Dodd, 2007).

The modelled farm economic analysis undertaken focused on the sheep enterprise, because it was assumed that investing in native shrubs on 10% of the farm only affected sheep feed supply, hence flock size causing changes in sheep enterprise cashflow. In the model, capital used to invest in the establishment and maintenance of the native shrubs was sourced internally from the sheep enterprise proceeds. Therefore, the sheep enterprise in the modelled farm comprised of cashflows from the established sheep flock enterprise and the native shrub investment.

Cashflows were discounted to forecast, over a 50-year period, the financial performance of the modelled native-shrub planting scenarios. Discounting cashflows is merited to account for the time value of money associated with investments (Herbohn & Harrison, 2002; Farrell, 2020). Annual net cashflows expressed as cash operating surplus (COS) were discounted at 7%, which is the rate used in cost benefit analysis of public investments and evaluation of small forestry projects in New Zealand (The Treasury, 2008) . Net present value (NPV) and break-even analysis were evaluated at three discount rates of 5%, 7% and 10%. The discount rates range considered uncertainties in discount rates with time as observed over the years with the business lending rates in New Zealand (Reserve Bank of New Zealand, 2021).

3.3.4. Sheep flock discounted cash operating surplus

The number of lambs sold from the sheep flock annually were the main drivers of the sheep enterprise COS. The 0% native shrub had a constant discounted sheep enterprise COS that decreased smoothly and was above that for 10% and 20% planting rates except in the initial five years of native shrub planting phase (Figure 19). The gradual drop in feed supply with withdrawal of land from grazing during the initial five years, caused more replacement ewe lambs to be sold that led to a higher sheep enterprise COS for the 10 and 20% planting rates than for 0% native shrubs but was higher for the 20% than the 10% planting rate. Sale of replacement ewe lambs in the initial five years led to a gradual decline in flock size across the age classes and was higher for 20% than 10% planting rate. The decline in flock size resulted in fewer lambs born and therefore sold, which explains the lower sheep enterprise COS for the two planting rates compared to 0% native shrubs, but which was higher for the 10% compared to 20% planting rate. The total withdrawal of 10% of the land from grazing (after 20 and 15years for 10% and 20% planting rates, respectively) led to a decrease in flock size and thus the lambs sold, explaining the observed marginal lower sheep enterprise COS for the two planting rates compared to the 0% native shrubs. Adjustment of flock size to meet the farm feed supply is a routine farm planning activity in hill country sheep and beef cattle farms and affects farm annual sheep enterprise COS (Beef+Lamb NZ, 2018a).

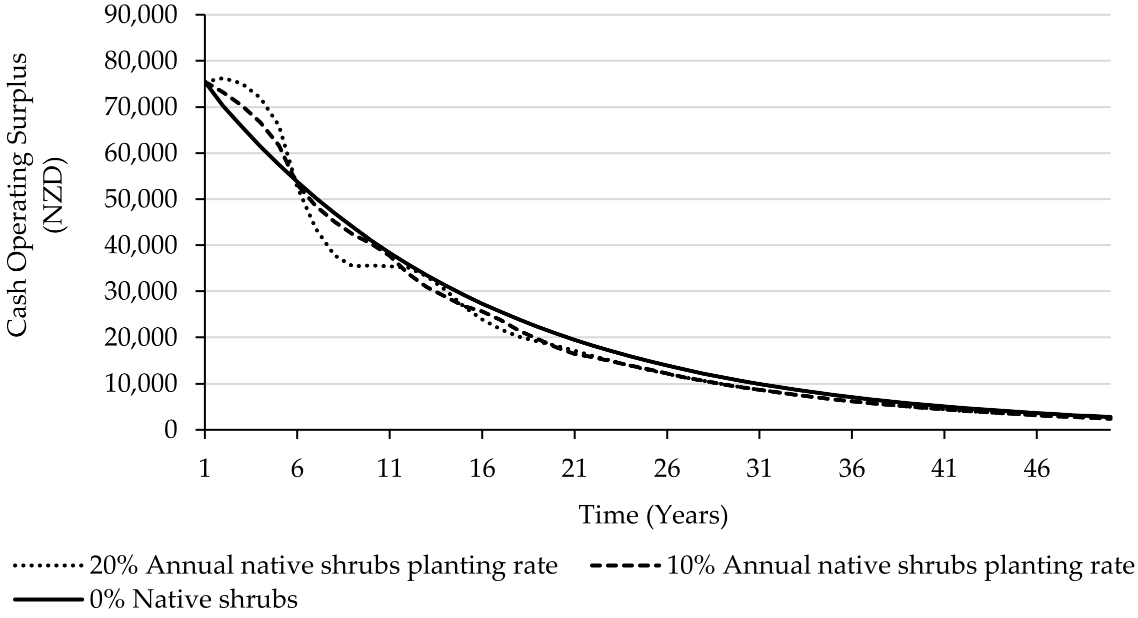

Figure 19. Annual sheep flock cash operating surplus (COS) discounted at 7% per year over 50 years for native shrubs planted on 10% of the modelled farm at 0%, 10% and 20% planting rates per year.

The conversion of 10% of the land to native shrub led to an overall higher mean annual sheep enterprise COS for the 0% native shrubs (NZ$ 22,270) scenario compared to the planting rates. Mean annual sheep enterprise COS was higher for the 10% (NZ$ 21,368) than 20% (NZ$ 21,199) planting rate. Combined, this data indicates that conversion of the 10% of the modelled farm to native shrubs led to a decrease in sheep enterprise COS explained by the reduction in overall flock size across time. A decline in sheep enterprise COS have been reported in New Zealand due to declining flock sizes as result of converting portions of hill country sheep and beef cattle farms to other farming enterprises such as dairy cattle, deer, plantation forestry and subdivision into smaller lifestyle blocks since 1990s (Campbell, 1973; Morris, 2014). However, a greater decline in sheep enterprise COS would be expected to occur when more productive low and medium slope land portions are withdrawn from sheep farming for other agricultural enterprises, compared to the non-utilizable steep slopes, due to their higher flock carrying capacity (Campbell, 1973; Morris, 2014). In these modelled scenarios steep slope areas were removed and planted in native shrubs.

3.3.5. Native shrubs cash flow

Discounted carbon income initially increased steadily and peaked at 10 and 12 years for the 10% and 20% planting rates, respectively, before gradually declining over the modelled period (Figure 20). The steady increase in carbon income over the initial time period resulted from the mean annual increase in the number of native shrubs planted and carbon accumulation while the gradual decline was due to decreasing mean carbon accumulation with native shrub age (Ministry for Primary Industries, 2017). Mean annual carbon income was marginally (1.17%) higher for the 20% (NZ$ 3,249) compared to the 10% (NZ$ 3,211) planting rates and can be attributed to higher carbon income for the first 8 years for the 20% native shrub planting rate, due to both a greater number of, and area planted in, native shrubs at that time. Similarly, mean annual native shrub establishment and maintenance expenses were 21% higher for the 20% (NZ$ 4,915) than 10% (NZ$ 4,056) planting rate due to the higher cost of establishment in the first five years for the 20% rate, but which were distributed over 10 years for the 10% planting rate. Overall, the establishment of native shrubs on 10% of the area of the modelled farm using either 10% or 20% native shrub planting rates per year had higher expenses relative to income. This suggests that the modelled carbon price (NZ$ 32/NZU) was too low to offset the costs associated with planting native shrubs.

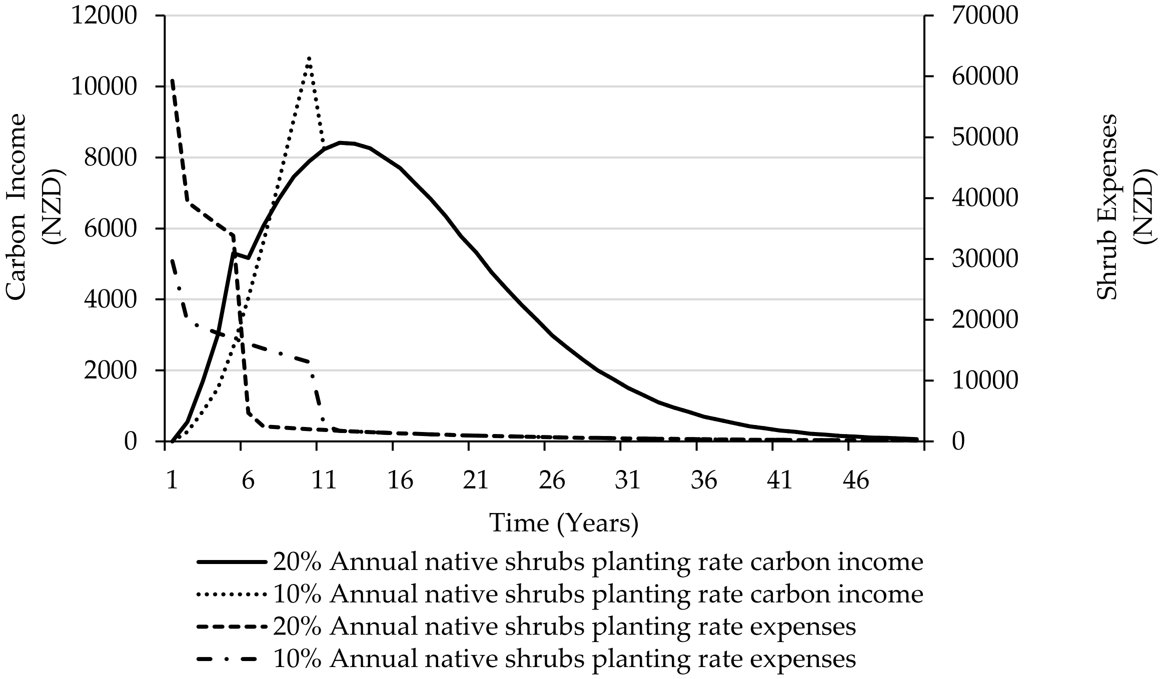

Figure 20. Total native shrub expenses and carbon income discounted at 7% per year over 50 years with native shrubs planted on 10% of the modelled farm at 0%, 10% and 20% planting rates per year.

3.3.6. Sheep enterprise discounted cash operating surplus.

Sheep enterprise (combined sheep flock COS and native shrub cash flow) COS for the different native shrub planting scenarios are shown in figure 21. A constant COS of the sheep enterprise with 0% native shrub was maintained as would be expected since the cashflow was unaffected by planting native shrubs. However, the reductions in sheep flock COS coupled with high planting expenses for the native shrubs led to a lower sheep enterprise COS with native shrubs at 10% and 20% planting rates in the initial 10 and 9 years, respectively, compared to the 0% native shrubs. However, the sheep enterprise COS with native shrubs exceeded that of 0% native shrubs when the cash income from carbon trade exceeded the shrub expenses (between 9 to 31 years and 10 to 31 years for the 20% and 10% planting rates, respectively). After 32 years there were marginal differences in sheep enterprise COS among the planting rate scenarios. Overall, mean annual sheep enterprise COS for 0% native shrubs (NZ$ 22,270) was higher by 7.9% and 12.3% than that with native shrubs at 10% (NZ$ 20,522) and 20% (NZ$ 19,532) planting rates, respectively. However, comparing sheep enterprise with 0% native shrubs to that with native shrubs revealed that, native shrub expenses caused a decrease in the sheep enterprise mean annual COS by 4.0% (NZ$ 21,368 vs NZ$ 20,522) and 7.9% (NZ$ 21,199 vs NZ$ 19,532) for 10% and 20% planting rates, respectively. High initial expenses mainly associated with seedling costs have been indicated as a prohibitive factor to the establishment of native shrubs on hill country farms in New Zealand (Pollock, 1986; Dodd, 2007; Bergin, 2014b). Although not explored in this study, grants supporting establishment of native shrubs in New Zealand can be used to offset the high initial cost of native shrubs establishment (Dodd, 2007; Fernandez, 2017; Saunders, 2017), which may have an impact on the total sheep enterprise COS.

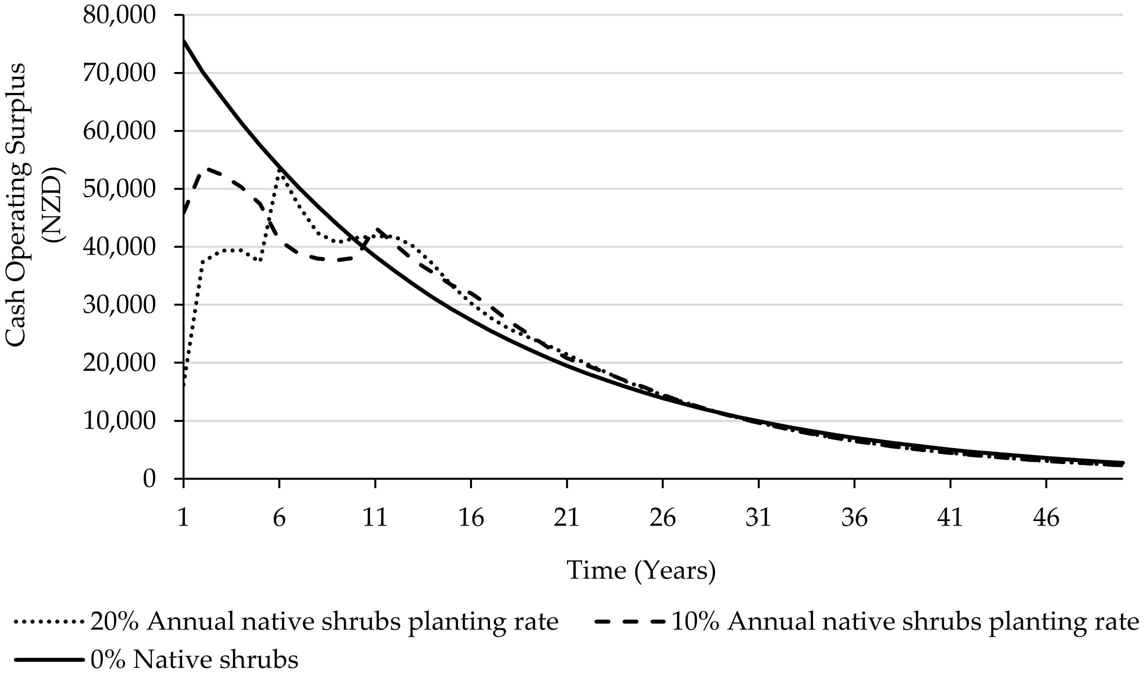

Figure 21. Annual sheep enterprise cash operating surplus (COS) discounted at 7% per year over 50 years for native shrubs planted on 10% of the modelled farm at 0%, 10% and 20% planting rates per year.

3.3.7. Sheep enterprise net present value (NPV) and Internal rate of return (IRR)

The NPV decreased with an increase in the COS discount rate (Table 9), an expected outcome, owing to their inverse relationship (Herbohn, 2002; Hopkinson, 2017). NPV was highest for the 0% native shrub compared to the planting rates but remained positive even at the very high discounting rate in all the modelled scenarios. Although a positive NPV signifies profitability in an investment in the long run (Hopkinson, 2017), the lower NPVs for the planting rates indicated that investing in the native shrubs on 10% of the farm at the modelled carbon market (NZ$ 32/NZU) would result in reduction of the sheep enterprise income. This can be explained by the observed drop in sheep flock cash inflow due to reduction in flock size and the high cash outflow due to native shrub establishment costs observed for the two planting rates.

Table 9. Net present value in New Zealand dollars (NZ$) at three discount rates (5%, 7% and 10%) for the sheep enterprise with native shrubs planted on up to 10% of the modelled farm on the steep slopes at 0%, 10% and 20% planting rates.

Planting Rate (%)	Discount Rate (%)			
	5	7	10	*50*[1]
0	1,546,937	1,191,563	879,919	*241,951*
10	1,423,384	1,072,865	764,458	167,786
20	1,342,444	991,635	683,174	100,157

[1] This discount rate was used to show NPV did not approach zero even at high values

However, only cashflows relating to carbon trade were considered in the model, despite native shrubs having other monetary and non-monetary benefits (Carver & Kerr, 2017). In addition, NPV assesses the financial profitability and viability of an investment using forecasted cashflows and does not consider non-monetary benefits that may arise over time (Hopkinson, 2017). Some potential non-monetary benefits from the planting of native shrubs on the farm can include, appreciating farm market value, reduction in erosion costs, biodiversity enhancement, landscape aesthetics, restoration of cultural values, and climate change mitigation through carbon sequestration (Dodd, 2007; Evison, 2008; Bergin, 2014b; Carver, 2017; Ministry for the Environment & Stats NZ, 2019). Further, the use of a single discount rate in the model assumes that the current agricultural policies and market would prevail unchanged throughout the modelled period. However, agricultural production can change with advancement in technology, consumer preferences, local and international market fluctuations which affects enterprises cashflows and therefore discount rates on capital (Rae et al., 2004; Smith & Montgomery, 2004). In New Zealand, the sheep population has been in decline due to the emergence of other agricultural enterprises while the meat and wool market trends have fluctuated over time due to reliance on export market and changes in policies locally and internationally (Rae, 2004; Smith, 2004; Morris, 2009). Although the two planting rates had lower NPV, the non-monetary value of native shrubs may outweigh those for the 0% native shrubs and requires further exploration.

The internal rate of return (IRR) is the measure of profitability which shows the rate at which an investment pays back to its capital (Crean, 2005) and was similar and approached infinity for all native shrub planting rates scenarios. This would be expected since there were no negative cashflows (Patrick & French, 2016) and no external source of capital was borrowed (Herbohn, 2002) to establish the native shrubs. Therefore, IRR could not be used to compare the native shrub planting regimes due to this limitation.

3.3.8. Break even analysis for native shrub investment on the model farm.

The carbon price required to obtain income equivalent to the status quo with 0% native shrub invested on 10% of the modelled farm, increased with increasing discount rate and native shrubs annual planting rates (Table 10). Overall, the break-even carbon price was higher than the modelled carbon price (NZ$ 32/NZU) for the native shrubs annual planting rate at all discount rates. This suggests that even with the modelled lowest return to capital of 5%, investing in native shrubs based on the modelled condition would not be financially attractive to hill country sheep and beef farms at the modelled carbon price. However, (Beef+Lamb NZ, 2020a) estimates a return to capital rate of 2.3% for investments in the East Coast region hill country (class 4) sheep and beef farm. Although not included in the study, running the model at a 2.3% discount rates resulted in break-even carbon market of NZ$ 44.90 and NZ$ 51.95 for the 10% and 20% planting rates respectively. This further implies that the modelled carbon market price (NZ$ 32/NZU) was still too low for farms investing in native shrubs on 10% of their land to financially break-even.

Increasing carbon price to above NZ$ 25 was suggested as an incentive for afforestation of the hill and hard hill country using radiata pine (Manley, 2019). However, radiata pine has nearly thrice the carbon sequestration potential, therefore higher carbon income compared to the native shrubs (Ministry for Primary Industries, 2017). In addition, radiata pine has additional cash inflow from logs and lower establishment costs (Bergin, 2014b; Carver, 2017) and therefore would have a lower break-even carbon price compared to native shrubs based on monetary benefits (Carver et al., 2018). High costs in native shrubs establishment can be averted by allowing natural revegetation but, this attracts higher risk of pest and weeds invasion that could affect survival of the juvenile native shrubs (Dodd, 2007; Carver, 2017) and would take substantially longer to occur. Suggested potential interventions that could enable hill country farms that are planting native shrubs to break-even include, setting a premium native vegetation carbon price, upfront native vegetation establishment financing and providing grants for establishing native vegetation (Carver, 2017).

Table 10. Break-even carbon price in New Zealand dollars per New Zealand unit (NZ$/NZU) of carbon at three discount rates (5%, 7% and 10%) for planting native shrubs on 10% of the modelled farm at 10% and 20% planting rates per year.

Planting Rate (%)	Discount Rate (%)		
	5	7	10
10	49.90	55.67	67.50
20	61.30	71.41	91.24

3.4. Conclusion

The study revealed that addition of a native shrub sub-model to the established hill country sheep and beef enterprise model, enabled partitioning of the archetype farm into the major slope types and their respective herbage productivity. Planting native shrubs on 10% of the farm on the steep slope caused a disproportionate decrease in overall mean annual farm feed supply by 6.6% and 7.1% for 20% and 10% planting rates, respectively relative to the 0% native shrub. The reduction in feed supply resulted in a 10.9% and 11.6% reduction in sheep flock size, which caused a decrease in sheep-only enterprise cash operating surplus by 4.1% and 4.8% for the 10% and 20% planting rates, respectively compared to 0% native shrubs. There were no greater differences in carbon income among the planting rates, but the native shrubs expenses were higher by 20% for 20% planting rate compared to the 10% planting rate. Overall, native shrubs expenses were higher than the carbon income and caused a further 4.0% and 7.9% reduction on the total sheep enterprise cash operating surplus for 10% and 20% planting rates, respectively. The net present value for all scenarios was positive and was higher for 0% native shrubs and least for 20% planting rate. Break-even carbon prices were higher than the modelled carbon price, indicating that a higher carbon price above the break-even price can make planting native shrub attractive to hill country sheep and beef cattle farms. The rapidly changing value of carbon price can be easily assessed using the model.

Forward to the Next Chapters

Developing the NSM sub-model in Chapter 3 highlighted data gaps in native shrubs that needed filling to enhance the sub-model's robustness. These gaps included native shrubs growth rate, biomass accumulation, partitioning of above ground biomass to various components, foliage production and nutritional composition, and carbon stock accumulation. These gaps were filled in subsequent chapters: Chapter 4 determined native shrubs foliage nutritional composition, Chapter 5 examined the fermentation characteristics and digestibility, and Chapter 6 addressed growth rate, biomass, foliage production, and carbon stock. The data collected in Chapters 4, 5 and 6 was used to update the NSM sub-model in Chapter 7.

Chapter 4: Nutritional Composition of New Zealand Native Shrubs Selected as Potential Forage for Ruminants

Abstract

Forage shrubs are an important feed resource used globally to meet livestock feed deficits. In New Zealand, fodder from willows and poplar, planted for erosion control in hill country sheep and beef farms, is occasionally used to supplement for metabolizable energy that is low in summer pastures. Although some New Zealand native shrubs are palatable and browsed by wild herbivores, their forage potential for farmed ruminants has not been explored. This study sought to determine the nutritional composition of leaf and stem of five native shrubs (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, *Pittosporum crassifolium* and *Pseudopanax arboreus*) and compare them to an osier willow (*Salix schwerinii*) within and across the seasons. The crude protein (CP) for all native shrubs leaves except *Hoheria populnea* were lower (< 10% DM) than required for maintenance of grazing animals. The foliage for all native species except *H. populnea* had superior metabolizable energy (ME) (> 11 MJ/ kg DM) than *S. schwerinii*. *Salix schwerinii* leaf was comparable to *H. populnea* in ME and CP in spring, but CP in summer was inferior. The stem nutritional composition for all the shrubs was comparable. In addition, the acid and neutral detergent fibres for both leaf and stem were within ranges found in pastures, fodder crops and forages in New Zealand. The findings from this study suggest that native shrubs can be a potential forage resource to supplement for low ME in summer pastures or to supply herbage in winter when pasture growth is low. However, further studies on native shrubs intake and preference by sheep are recommended.

Key Words: New Zealand native shrubs, *Salix schwerinii*, nutritional composition

4.1. Introduction

Forage shrubs are an important feed resource that can be used to lessen feed deficits in areas that experience seasonal pasture quantity and quality fluctuations (Eichhorn et al., 2006; De Koning & Milthorpe, 2008). In arid and semi-arid pastoral grazing systems, shrub browse is a major feed supply particularly during the dry seasons when herbaceous pastures senescence (Topps, 1992; De Koning, 2008; Kökten et al., 2012; Akbag, 2021). Forage shrubs integrated in agroforestry often provide non-conventional supplementary feed in mixed crop and livestock farming systems (Devendra & Sevilla, 2002; Amata, 2014; Gachuiri et al., 2017; Vandermeulen et al., 2018). However, in temperate regions, such as New Zealand, where climatic conditions can generally support year-round growth of pastures, use of forage shrubs as feed resource is commonly of a secondary role (Kemp, 2003; Eichhorn, 2006; McIvor, 2006; Vandermeulen, 2018). As a result, shrubs and trees have progressively been cleared for pasture expansion (Eichhorn, 2006), leading to negative impacts on the environment (Wedderburn et al., 2020). However, the role of forage shrubs and trees in providing ecosystem services with an additional role as supplementary feed resource in the pastoral farming landscapes in New Zealand is gradually being acknowledged (Lefroy et al., 1992; Dickinson, 2015; Vandermeulen, 2018).

New Zealand pastoral farming is dominated by sheep and beef cattle that rely on pastures for more 95% of their dietary requirements (Pain et al., 2015). More than half of these farms are classified as hill country and are characterized by flat (11%), rolling (32%) and steep slopes (40%) (Beef+Lamb NZ, 2020b). Hill country topography influences pasture composition, distribution and production (Radcliffe, 1982). The flat and rolling areas contain improved pastures mainly a mix of perennial ryegrass and white clover pasture (Beef+Lamb NZ, 2020b) while the steep slopes are mostly unimproved and have high proportions of Browntop, Yorkshire fog and sweet vernal pastures (Radcliffe, 1982; Waghorn & Clark, 2004). However, the quality and quantity of the pastures deteriorate during summer and autumn seasons, which coincides with increased feed demand for lambs and calves weaning and ewe flushing and steaming up, respectively (Beef+Lamb NZ, 2018a). Pasture quality deterioration is greatest on the steep slopes of hill country farms (Hodgson, 2005; Kemp, 2016).

On the steep slopes there is limited ability to plant and utilize improved pastures because of the thin soil, poor fertility, low moisture and high vulnerability to soil mass movement (Kemp, 2016). A common option on the steep slopes is the use of exotic willows and poplar that are primarily planted for erosion control and wind breaks (Wilkinson, 1999) but can supply supplemental fodder when coppiced or browsed (Pitta, 2007; Benavides, 2009). However, willows and poplar are deciduous (Benavides, 2009) limiting their supplemental feed supply only to during spring and summer seasons (Pitta, 2007). Exotic forest species such as radiata pine may also be planted for timber production (Benavides, 2009) but offer no nutritive value to ruminants and expose the steep slopes to cyclic soil mass movement during harvesting (Cairns, 2001). A further recent option is to integrate native shrubs on steep slopes because they offer the ecosystem services provided by the exotic species and provide fodder or browse, but their value to livestock have not been fully explored (Dodd, 2007; Dickinson, 2015).

Native shrubs account for approximately 16% of New Zealand indigenous flora and comprises more than 400 taxa of which, most are endemic (Merrett, 2006; Kerr, 2014). They are evergreen and can be used as a refuge for vulnerable livestock during cold or wet weather. Native shrubs with forage potential can supply supplemental fodder or browse when pasture growth and quality are low, especially during summer and winter. Additionally, native shrubs can provide several benefits for hill country farmers including erosion control, increased indigenous biodiversity and carbon sequestration (Pannell, 2021). Some of New Zealand native shrubs are palatable and highly preferred by deer and wild herbivores (Mitchell, 1987; Nugent, 1990; Forsyth, 2002; Bee et al., 2007, 2011). However, the nutritive value of the potential forage native shrubs to farmed ruminants in New Zealand have not been widely investigated (Lambert et al., 1989b; Dickinson, 2015). Profiling the nutritional composition of some potential forage native shrubs is of benefit to hill country sheep and beef farmers, policy makers and researchers as it will likely impact the selection of shrubs for hill country landscape management and improvement. The purpose of this study was to evaluate the nutritional composition of some New Zealand native shrubs with potential to provide forage for ruminants. Specifically, the study objectives were to determine the proximate nutritional composition of edible leaf and stem of five native shrubs (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, *Pittosporum crassifolium* and *Pseudopanax arboreus*) and an exotic osier willow (*Salix schwerinii*) and to compare them across and within the seasons.

4.2. Materials and Methods

4.2.1. Description of shrub species used in the study

The term shrub in this study was used to refer to woody plants with a bushy growth habit, that differ from trees chiefly in height (David & Mikaila, 2008). All the native shrubs used in the study are endemic to New Zealand but varied in taxonomy and physiognomy. *Coprosma robusta* (Karamū) is among the widely distributed native shrubs in New Zealand due to its fast growth and colonizing nature (de Lange, 2022a). It belongs to Rubiaceae family and is characterized by numerous branches, glabrous elliptical leaves and an erect or spreading growth of up to 6 m (Metcalf, 2011). *Griselinia littoralis* (Pāpāuma) is a heavily branched erect shrub growing up to 15 m and belongs to the Griseliniaceae family (Salmon, 1996; Metcalf, 2011). The shrub has glossy rounded leaves that are paler underneath and attached to yellow pigmented branchlets (Metcalf, 2011). *Hoheria populnea* (Houhere) belongs to the Malvaceae family (Metcalf, 2011), has an erect or spreading growth of up to 9 m and serrated ovate leaves and maroon tinted petioles and leaf veins (de Lange, 2022b). *Pittosporum crassifolium* (Karo) belongs to the Pittosporaceae family and grows up to 9 m as an erect heavily branched shrub with characteristic wooly tomentum on branchlets and underside of leaves (Salmon, 1996; Metcalf, 2011; de Lange, 2022d). *Pseudopanax arboreus* (Five Finger) is a muti-branched shrub growing up to 8 m belonging to Araliaceae family (de Lange, 2022e). However, unlike the other native shrubs, *P. arboreus* has palmate leaves with five leaflets, is dioecious and frequently epiphytic (Salmon, 1996; Metcalf, 2011). *Salix schwerinii* (Kinuyanagi) is an osier willow in the Salicaceae family that is exotic to New Zealand (McIvor, 2006). It is characterized by spreading multi-stemmed growth of up to 6 m and has dense silvery pubescence on branchlets and its linear leaves (MacIvor et al., 2005; McIvor, 2006). Unlike the five native species which are evergreen, *S. schwerinii* is deciduous.

4.2.2. Study sites description

The shrub samples used in the study were collected from a trial site on Massey University Dairy4 in Palmerston North. Massey University Dairy4 farm is located five kilometers south of Palmerston North city. The long-term climatic conditions for Palmerston North district (Chappell, 2015) are defined in Table 11. The trial site on Dairy4 farm was located (Lat -40.401447, Long 175.617912) on a steep slope (>25°) with a southerly aspect. Dominant soil types at the trial site were Tokomaru silt loam soil at the top and Ohakea silt at the bottom of the slope and were characterized by an average natural fertility and fair to poor drainage (Cowie & Rijkse, 1977). The trial site was set up in a randomized complete block design (RCBD) of four blocks in a two-by-two block arrangement and each block had eight plots. Eight trial shrub species consisting of five native shrubs (*C. robusta*, *G. littoralis*, *H. populnea*, *P. crassifolium* and *P. arboreus*), two native species Hawkes Bay ecotypes (*G. littoralis* and *P. arboreus*) and an exotic osier willow (*S. schwerinii*) were randomly allocated to the plots in each of the blocks, such that all the four blocks had all eight shrubs. Each of the plots had a total of 15 shrubs, planted in three rows and five columns, and spaced at 1.5m by 1.5m apart. Prior to planting, the site was used for dairy cattle grazing.

Table 11. Summarized long-term seasonal climatic conditions for the Palmerston north district (Chappell, 2015)

Climate parameters		Season			
		Summer	Autumn	Winter	Spring
Temperature	Mean (°C)	17.4	13.8	9.0	12.4
	Total (mm)	222.0	189.0	246.0	43.7
Rainfall	Percent of total rainfall (%)	25.0	21.0	27.0	26.0
	Average monthly rain days (d)	11.7	12.7	17.7	15.3

4.2.3. Sample collection and processing

Seedlings for the native species and poles for *S. schwerinii* were planted on Massey University Dairy4 trial site during the winter season in August 2019. Foliage samples from the trial site were collected during the summer and spring of 2020 and the winter of 2021 corresponding to approximately 390, 430 and 760 days after planting, respectively. The foliage samples were leaved stems with a diameter of less than 5 mm. Foliage with diameter of less than 5 mm contain mostly new growth and soft stem that sheep can consume (Karachi, 1998; Kemp, 2001). Five shrubs in each plot were randomly selected and foliage samples harvested and pooled. The foliage samples were indiscriminately harvested from the lower, middle and the top parts (not higher than 1.1m) of the shrub to imitate the browsing behavior of the sheep (Sanon, 2007) and to ensure the samples were representative of the entire shrub to the height of sheep browsing. All the other shrubs were sampled from the trial site except the Hawkes Bay ecotypes for all seasons and *S. schwerinii* in winter due to inadequate herbage availability.

4.2.4. Sample processing

Collected foliage samples were labeled, and chilled to approximately 4°C while being processed. Any foreign materials such as grass, dead leaves and non-plant matter were removed before separating the foliage samples into leaf and stem sub-samples. The leaf sub-sample consisted of the leaf blade, stipules, buds, and petiole, while the stem sub-sample included the woody and soft bark where the leaves were attached. The sub-samples were frozen before submission to the Massey University Food and Nutrition Laboratory for freeze drying, grinding and proximate nutritional composition analysis.

4.2.5. Proximate nutritional composition analysis and in vitro digestibility

The leaf and stem sub-sample dry matter content (DM) was determined as percentage of the weight remaining after moisture loss during freeze drying and was estimated using the AOAC (Association of Official Agricultural Chemists) 925.10, 930.15 calculation. Pyrolysis and combustion following AOAC 968.06 (Dumas) method was used to estimate total nitrogen, which was multiplied by 6.25 to estimate the crude protein (CP) content in the sub-samples (Waghorn et al., 2017). Ash content was determined by combusting the organic matter (OM) portion of the DM in a Furnace at 550°C following the AOAC 942.05 (Feed, meat) method. Fibre fractions were estimated following AOAC 2002.04 method for neutral detergent fibre (NDF) and AOAC 973.18 for acid detergent fibre (ADF) and acid detergent lignin (ADL) using the Fibretec system.

In vitro dry matter digestibility (IVDMD) and organic matter digestibility (IVOMD) were estimated by treating samples with neutral detergent solution and digesting with pepsin and fungal cellulase enzymes as described by (Roughan & Holland, 1977) and were expressed as percentage of the DM. Digestible organic content in the dry matter (IVDOMD) was calculated as a product of sub-sample OM (100- ash) and IVOMD and expressed as a percentage of the DM. The IVDOMD was used to derive the metabolizable energy (ME) in megajoules per kilogram of DM (MJ/kg DM) by multiplying with a factor of 0.16 (Agricultural and Food Research Council (Great Britain), 1993).

4.2.6. Statistical analysis

The MIXED procedure of SAS software (Version 9.4, SAS Institute Inc. Cary, NC, USA) was used in the data analysis. Data was organized in a randomized complete block design statistical model (Equation 10) with sampled shrubs as replicates. The model consisted of nutritional composition (y) as the response variable that was affected by shrub species sub-samples (leaf or stem) (S_T) and season (spring, summer, and winter) (W) as the main effects, their two-way interaction ($S_T \times W$) and block (B) as the fixed effect. However, the model was run separately for the leaf and stem because the leaf and edible stem of woody plants are morphologically distinct plant parts and vary in structure and nutritional composition.

Equation 10 $$y_{ijk} = S_{T_i} + W_j + (S_{T_i} \times W)_{ij} + B_k$$

The main effects, their two-way interaction, and the block effect on the nutritional composition was determined using the least squares means method at α=0.05 and the different means were separated using the Tukey post hoc test. Since *S. schwerinii* is deciduous and no foliage was collected in the winter season, only the spring and summer seasons data were used for the species in the statistical analysis.

4.3. Results

1.1. Shrubs main effects on nutritional composition

Table 12 shows a summary of the shrub main effect on nutritional composition. Shrub sub-sample (leaf or stem) and season showed a significant ($p<0.05$) two-way interaction on the chemical composition. In addition, blocking reduced the variability of nutritional composition for the leaf and stem, except for the leaf ME and stem ash content.

Table 12. Statistical inference for the main effects of shrub samples (leaf and stem) and season, their interactions, and the fixed effect of block on the nutritional composition (dry matter (DM,% wet weight), ash (Ash,% DM), crude protein (CP,% DM), acid detergent fibre (ADF,% DM), neutral detergent fibre (NDF,% DM), lignin (Lignin,% DM) and metabolizable energy in mega joules per kilogram of DM (ME, MJ/kg DM)).

Nutrients	Leaf	Season	Leaf× Season	Block	Stem	Season	Stem× Season	Block
DM (% wet weight)	***	***	***	*ns*	***	***	*	*ns*
Ash (% DM)	***	**	***	*ns*	***	*ns*	***	****
CP (% DM)	***	***	***	*ns*	***	**	***	*ns*
ADF (% DM)	***	***	**	*ns*	***	***	*	*ns*
NDF (% DM)	***	***	***	*ns*	***	***	**	*ns*
Lignin (% DM)	***	**	*	*ns*	***	*ns*	*	*ns*
ME (MJ/ kg DM)	***	***	***	*	***	*ns*	***	*ns*

Statistical inference for main effects, their interaction and block effects on the nutritional composition for leaf or stem. *** significant at p<0.001, ** p<0.01, * p<0.05 and *ns* not significant p>0.05.

4.3.1. Leaf nutritional composition by season

The dry matter (DM) content was unaffected by season for *C. robusta* and *S. schwerinii* but was in general higher ($p<0.05$) in winter and lower ($p<0.05$) in summer season for all the other shrub species (Table 13). However, the DM for *P. crassifolium* was similar ($p>0.05$) in spring and in winter while that for *G. littoralis* and *P. arboreus* did not differ ($p>0.05$) to any other season.

Table 13. Leaf nutritional composition: Dry matter (DM,% fresh weight), ash (Ash,% DM), crude protein (CP,% DM), neutral detergent fibre (NDF,% DM), acid detergent fibre (ADF,% DM) and lignin (Lignin,% DM) and metabolizable energy in megajoules per kilogram of DM (ME, MJ/kg DM) among seasons (spring, summer and winter) for the native (*C. robusta, G. littoralis, H. populnea, P. crassifolium* and *P. arboreus*) and exotic (*S. schwerinii*) shrub species.

Shrub	DM	Ash	CP	ADF	NDF	Lignin	ME
Spring							
Coprosma robusta	39.3^{ab}	7.0^{b}	8.0^{b}	22.4^{ab2}	37.5^{a1}	9.6^{ab}	12.0^{a12}
Griselinia littoralis	31.6^{c12}	7.3^{b}	6.2^{bc}	22.3^{ab}	32.1^{a1}	12.0^{a}	11.9^{ab}
Hoheria populnea	31.1^{c2}	11.6^{a2}	14.0^{a1}	20.2^{ab2}	37.6^{a1}	7.5^{b}	11.4^{bc1}
Pittosporum crassifolium	43.0^{ab1}	6.5^{b2}	6.2^{bc}	20.7^{ab2}	36.4^{a1}	9.3^{ab}	11.9^{ab1}
Pseudopanax arboreus	39.5^{ab12}	6.7^{b}	5.3^{c}	15.6^{b}	22.4^{b}	8.3^{ab}	12.4^{a}
Salix schwerinii	43.1^{a}	4.9^{c}	15.1^{a1}	24.6^{a2}	36.3^{a2}	8.9^{ab2}	11.3^{c1}
Summer							
Coprosma robusta	35.6^{cb}	7.3^{bc}	7.7^{b}	24.5^{b2}	34.6^{bc1}	12.0^{ab}	11.5^{bc2}
Griselinia littoralis	31.0^{cd2}	7.2^{bc}	6.2^{bc}	22.3^{bc}	31.0^{c1}	13.0^{ab}	11.7^{abc}
Hoheria populnea	28.2^{d2}	11.7^{a2}	11.2^{a2}	24.9^{b2}	39.1^{b1}	7.3^{c}	10.4^{d2}
Pittosporum crassifolium	37.8^{ab2}	8.3^{b1}	7.3^{bc}	20.0^{bc2}	30.3^{c12}	9.1^{bc}	11.2^{c2}
Pseudopanax arboreus	36.0^{bc2}	6.2^{cd}	5.4^{c}	15.4^{c}	21.6^{d}	9.2^{bc}	12.2^{ab}
Salix schwerinii	42.4^{a}	5.5^{d}	8.3^{b2}	35.0^{a1}	50.0^{a1}	13.4^{a1}	10.5^{d2}
Winter							
Coprosma robusta	38.0^{b}	7.0^{b}	9.6^{b}	34.1^{a1}	24.5^{a2}	13.1^{a}	12.2^{a1}
Griselinia littoralis	36.3^{b1}	6.9^{b}	7.2^{c}	30.6^{a}	20.8^{a2}	12.5^{a}	12.2^{a}
Hoheria populnea	41.2^{b1}	13.1^{a1}	13.5^{a1}	36.5^{a1}	20.4^{a2}	6.6^{b}	10.6^{c2}
Pittosporum crassifolium	46.8^{a1}	7.3^{b12}	7.5^{bc}	38.1^{a1}	24.8^{a2}	10.1^{ab}	11.6^{b12}
Pseudopanax arboreus	41.3^{b1}	7.1^{b}	5.6^{c}	21.7^{b}	16.8^{b}	8.7^{b}	12.3^{a}

Specific nutrient values for each shrub with different numeral superscripts differs between seasons at p< 0.05. Specific nutrient values with different letter superscripts within a season are different at p< 0.05

Ash content differed ($p<0.05$) among the seasons for only *H. populnea* and *P. crassifolium*. Crude protein (CP) differed ($p<0.05$) among the seasons for only *H. populnea* and *S. schwerinii*, which had higher ($p<0.05$) CP in the spring season. Acid detergent fibre (ADF) did not differ among seasons for *G. littoralis* and *P. arboreus*. However, ADF was lower ($p<0.05$) and did not differ ($p>0.05$) between summer and spring seasons for all the other native species. Neutral detergent fibre (NDF) was higher ($p<0.05$) and for all native species except for *P. arboreus. Pseudopanax arboreus* NDF was not different ($p>0.05$) across the seasons, while that for all the other shrubs was similar ($p>0.05$) for the spring and summer seasons. The ADF and NDF were higher ($p<0.05$) in summer than in spring for *S. schwerinii*. Lignin content in the native species was not affected by season ($p>0.05$) but was higher ($p<0.05$) in summer than spring for *S. schwerinii*. All shrubs had lower ($p<0.05$) ME in summer except for *G. littoralis* and *P. arboreus* which were not influenced by season ($p>0.05$).

4.3.2. Seasonal leaf nutritional composition

4.3.2.1. Spring

Salix schwerinii had higher ($p<0.05$) and *H. populnea* and *G. littoralis* lower ($p<0.05$) DM than all the other shrub species, which did not differ ($p>0.05$) (Table 13). Ash content was higher ($p<0.05$) in *H. populnea* and lower ($p<0.05$) in *S. schwerinii* than all the other shrub species, which were not different ($p>0.05$). The CP was higher ($p<0.05$) in *H. populnea* and *S. schwerinii* leaves and lower ($p<0.05$) in *P. arboreus* than in all the other shrub species. *Salix schwerinii* leaves had higher ($p<0.05$) and *P. arboreus* lower ($p<0.05$) ADF than all other shrubs. The remaining shrubs ADF was similar ($p>0.05$) and did not differ ($p>0.05$) with either *S. schwerinii* or *P. arboreus*. The NDF was lower ($p<0.05$) for *P. arboreus* than all the other shrubs, which did not differ ($p>0.05$). Lignin was higher ($p<0.05$) in *G. littoralis* and lower ($p<0.05$) in *H. populnea* leaves than all the other shrubs, which were not different ($p<0.05$) from any other shrub. The ME was higher ($p<0.05$) for *C. robusta* and *P. arboreus* and lower ($p<0.05$) for *S. schwerinii* leaves than in all other shrub species.

4.3.2.2. Summer

Foliage DM was higher ($p<0.05$) for *S. schwerinii* and lower ($p<0.05$) for *H. populnea* than all the other shrub species. Ash content was higher ($p<0.05$) in *H. populnea* and lower ($p<0.05$) in *S. schwerinii* than in all the other shrub species. *Hoheria populnea* had higher ($p<0.05$) and *P. arboreus* lower ($p<0.05$) CP than all the other shrubs. The ADF and NDF were higher ($p<0.05$) in *S. schwerinii* and lower ($p<0.05$) in *P. arboreus* than in all the other shrubs. However, the ADF for *G. littoralis* and *P. crassifolium* did not differ ($p>0.05$) to that of *P. arboreus*. Lignin was higher ($p<0.05$) in *S. schwerinii* and lower ($p<0.05$) in *H. populnea* than in all the other shrub species. *Hoheria populnea* and *S. schwerinii* had similar ($p>0.05$) but lower ($p<0.05$) ME than all the other shrub species.

4.3.2.3. *Winter*

During the winter season, *P. crassifolium* had higher ($p<0.05$) DM than all the other shrub species, which were similar ($p>0.05$). Ash content was higher ($p<0.05$) for *H. populnea* leaves than all the other shrub species, which were not different ($p>0.05$). The CP was higher ($p<0.05$) in *H. populnea* and lower ($p<0.05$) in *G. littoralis* and *P. arboreus* than in all the other shrub species. *Pseudopanax arboreus* had lower ($p<0.05$) ADF and NDF than in all the other shrub species, which did not differ ($p>0.05$). Lignin content was lower ($p<0.05$) in *H. populnea* and *P. arboreus* than in all other shrub species, except *P. crassifolium* which was not different ($p>0.05$) to any other shrub species. The ME was lower ($p<0.05$) for *H. populnea* followed by *P. crassifolium* than other shrub species which were not different ($p>0.05$).

4.3.3. Seasonal stem nutritional composition

The stem nutritional composition varied ($p<0.05$) among seasons for the shrub species except for lignin (Table 14). Stem DM did not differ ($p>0.05$) among seasons for *C. robusta*, *G. littoralis* and *S. schwerinii* but was lower ($p<0.05$) for all the other shrub species during the summer season. There were no differences ($p>0.05$) among seasons in ash content for remaining shrub species except for *H. populnea* and *P. crassifolium*. Both *H. populnea* and *P. crassifolium* had higher ($p<0.05$) ash in summer and lower ($p<0.05$) in spring. However, the ash content for *P. crassifolium* did not differ ($p>0.05$) between spring and winter, while *H. populnea* ash in winter was not different ($p>0.05$) to the other seasons. The CP was similar ($p>0.05$) in all seasons for all shrub species except for *C. robusta* and *S. schwerinii*. *Coprosma robusta* CP was higher in winter ($p<0.05$) and lower ($p<0.05$) in summer and was not different ($p>0.05$) to the other seasons in spring. However, *S. schwerinii* CP was higher ($p<0.05$) in spring than in summer. The ADF did not differ ($p>0.05$) in all the seasons for *C. robusta*, *P. arboreus* and *S. schwerinii* stems but was higher ($p<0.05$) in winter and lower ($p<0.05$) and similar ($p>0.05$) in summer and in spring for all the other shrub species. Native species had higher ($p<0.05$) NDF which did not differ ($p>0.05$) between spring and summer seasons. However, the NDF for *H. populnea* and *P. arboreus* in summer was not different ($p>0.05$) to other seasons. *Salix schwerinii* NDF did not differ ($p>0.05$) between summer and spring seasons. There were no species differences ($p>0.05$) in stem ME in all the seasons except for *C. robusta* and *H. populnea*. The ME for all shrub species except *H. populnea* and *C. robusta* was not different ($p>0.05$) among seasons. However, *H. populnea* ME was higher ($p<0.05$) and did not differ ($p>0.05$) between spring and summer while *C. robusta* had higher ($p<0.05$) ME in winter and lower ($p<0.05$) in summer.

Table 14. Stem nutritional composition: Dry matter (DM,% fresh weight), ash (Ash,% DM), crude protein (CP,% DM), neutral detergent fibre (NDF,% DM), acid detergent fibre (ADF,% DM) and lignin (Lignin,% DM) and metabolizable energy in megajoules per kilogram of DM (ME, MJ/kg DM) among seasons (spring, summer and winter) for the native (*C. robusta, G. littoralis, H. populnea, P. crassifolium* and *P. arboreus*) and exotic (*S. schwerinii*) shrub species.

Shrub	DM	Ash	CP	ADF	NDF	Lignin	ME
			Spring				
Coprosma robusta	35.8^{c}	6.4^{b}	4.7^{b12}	36.7^{a}	46.6^{a1}	9.1^{abc}	10.2^{ab12}
Griselinia littoralis	32.1^{c}	5.6^{b}	4.1^{b}	38.6^{a2}	48.6^{a1}	10.2^{ab}	10.0^{ab}
Hoheria populnea	36.0^{c12}	9.0^{a2}	8.3^{a}	41.5^{a2}	53.5^{a1}	9.3^{abc}	9.6^{b1}
Pittosporum crassifolium	47.4^{ab1}	6.8^{b2}	4.2^{b}	41.0^{a2}	52.1^{a1}	8.8^{bc}	9.6^{b}
Pseudopanax arboreus	37.1^{bc1}	9.1^{a}	3.6^{b}	27.7^{b}	37.4^{b1}	7.4^{c}	10.4^{a}
Salix schwerinii	48.5^{a}	3.7^{c}	7.0^{a1}	38.4^{a}	48.9^{a}	11.6^{a}	10.2^{ab}
			Summer				
Coprosma robusta	29.4^{b}	5.7^{c}	4.2^{bc2}	36.9^{a}	47.9^{a1}	8.0^{b}	9.9^{b2}
Griselinia littoralis	29.6^{b}	5.0^{cd}	3.4^{bc}	39.2^{a2}	48.6^{a1}	12.3^{a}	9.9^{b}
Hoheria populnea	29.0^{b2}	10.9^{a1}	9.3^{a}	35.4^{a2}	46.3^{a12}	9.6^{b}	9.6^{b1}
Pittosporum crassifolium	35.1^{ab2}	8.9^{b1}	4.8^{b}	39.2^{a2}	48.3^{a1}	9.7^{b}	9.5^{b}
Pseudopanax arboreus	26.2^{b2}	7.8^{b}	2.6^{c}	26.5^{b}	34.3^{b12}	8.1^{b}	10.8^{a}
Salix schwerinii	41.8^{a}	3.9^{d}	3.7^{bc2}	40.2^{a}	53.3^{a}	12.9^{a}	10.1^{b}
			Winter				
Coprosma robusta	32.3^{b}	6.8^{c}	6.3^{b1}	40.0^{b}	30.7^{bc2}	7.1^{c}	10.7^{a1}
Griselinia littoralis	37.0^{ab}	6.0^{c}	3.6^{c}	50.9^{a1}	40.0^{a2}	11.7^{a}	9.8^{b}
Hoheria populnea	45.5^{a1}	9.9^{a12}	8.8^{a}	51.6^{a1}	41.4^{a2}	10.1^{ab}	8.8^{c2}
Pittosporum crassifolium	44.7^{a12}	7.4^{bc2}	4.4^{bc}	50.3^{a1}	38.6^{ab2}	8.6^{bc}	9.7^{b}
Pseudopanax arboreus	33.9^{ab12}	8.9^{ab}	3.6^{c}	35.8^{b}	27.7^{c2}	8.2^{bc}	10.7^{a}

Specific nutrient values for each shrub with different numeral superscripts differs between seasons at $p< 0.05$. Specific nutrient values with different letter superscripts within a season are different at $p< 0.05$

4.3.4. Within season stem nutritional composition

4.3.4.1. Spring

The DM was higher ($p<0.05$) for *S. schwerinii* than for the native species (Table 14). *Hoheria populnea* and *P. arboreus* stems had higher ($p<0.05$) and *S. schwerinii* lower ($p<0.05$) ash content than all other species, which were not different ($p>0.05$). *Hoheria populnea* and *S. schwerinii* had higher ($p<0.05$) CP than all other species, which did not differ ($p>0.05$). *Pseudopanax arboreus* contained lower ($p<0.05$) ADF and NDF than all other species, which did not differ ($p>0.05$). Lignin content was higher ($p<0.05$) for *S. schwerinii* and lower ($p<0.05$) for *P. arboreus* stems than all other species. *Pseudopanax arboreus* had higher ($p<0.05$) while *H. populnea* and *P. crassifolium* had lower ($p<0.05$) ME than all other species. However, the remaining shrub species ME was not different ($p>0.05$) to that *P. arboreus*, *H. populnea* and *P. crassifolium*.

4.3.4.2. Summer

Salix schwerinii had higher ($p<0.05$) DM than the native species in summer. Ash content was higher ($p<0.05$) for *H. populnea* and lower ($p<0.05$) for *S. schwerinii* stems than in all other species. The CP was higher ($p<0.05$) for *H. populnea*, followed by *P. crassifolium* and lower ($p<0.05$) for *P. arboreus*, while the other shrub species did not differ ($p>0.05$) from *P. crassifolium* and *P. arboreus*. The ADF and NDF were lower ($p<0.05$) for *P. arboreus* stems than for remaining species, which were similar ($p>0.05$). Lignin content was similar ($p>0.05$) for *G. littoralis* and *S. schwerinii* and higher ($p<0.05$) than for remaining species, which did not differ ($p>0.05$). *Pseudopanax arboreus* had higher ($p<0.05$) ME than all the other shrubs, which were not different ($p>0.05$).

4.3.4.3. Winter

During the winter, *P. crassifolium* and *H. populnea* stems had similar ($p>0.05$) and higher ($p<0.05$) DM and *C. robusta* had lower ($p<0.05$), while the remaining species did not differ ($p>0.05$). The ash content was higher ($p<0.05$) for *H. populnea* and lower ($p<0.05$) for *C. robusta* and *G. littoralis* than for all other species. *Hoheria populnea* had higher ($p<0.05$) and *G. littoralis* and *P. arboreus* lower ($p<0.05$) CP than for all other species. The ADF was lower ($p<0.05$) for *C. robusta* and *P. arboreus* than for all other species, which did not differ ($p>0.05$). *Pseudopanax arboreus* had lower ($p<0.05$) NDF than for all other species. Lignin content was higher ($p<0.05$) for *G. littoralis* and lower

($p<0.05$) for *C. robusta* than for all shrub species. The ME content was similar ($p>0.05$) and higher ($p<0.05$) for *C. robusta* and *P. arboreus,* respectively and lower ($p<0.05$) for *H. populnea* than for all the other shrubs, which were not different ($p>0.05$).

4.4. Discussion

This study sought to evaluate and compare the nutritional composition of the leaf and edible stem components of five native shrubs and an exotic osier willow (*S. schwerinii*) across and within the seasons. The five native shrubs are endemic to New Zealand and often found on reserves and unutilized parts of hill country sheep and beef cattle farms. They are known to be palatable and browsed by wild herbivores (Mitchell, 1987; Nugent, 1990; Forsyth, 2002; Bee, 2007, 2011). *Salix schwerinii* has been used in hill country sheep and beef cattle farms primarily for soil conservation and also as a source of supplementary fodder (Oppong, 2001; Pitta, 2007; Douglas, 2009). It is possible that native shrubs could be used for the same purpose. A bioeconomic modelling study (Chapter 3) suggested that if native shrubs are used in this manner they can provide sufficient supplemental forage for sheep, especially during summer when pastures quality is low. However, the estimation of herbage production in this model was based on sparse data available (Chapter 3). It is known that sheep will browse willow leaf and stem up to 5 mm diameter (Oppong, 2001; Kemp, 2003; Pitta, 2007). Therefore, it is of benefit to gain a greater understanding of the nutritional composition of native shrub leaf and stem to determine their potential use as supplemental forage on hill country sheep and beef farms in New Zealand.

4.4.1. Seasonal variation in leaf nutritional composition

The nutritional composition of *S. schwerinii* leaf was different to that of native shrubs in both spring and summer. Further, native shrubs were also contrasting in nutritional composition in all seasons. *Salix schwerinii* varied in CP, ADF, NDF, lignin and ME between spring and summer while most native species leaf showed variability in DM, ADF, NDF and ME but not lignin across the seasons. Among the native shrubs, *H. populnea* showed the greatest variability while *P. arboreus* the least variability in nutritional composition across the seasons. The nutritional variability between spring and summer for *S. schwerinii* and across the seasons for the native shrubs can be attributed to their differences in phenological responses to seasonal changes in ambient conditions (Chapman et al., 2014; González-Zurdo et al., 2016). *Salix schwerinii* is deciduous

(McIvor, 2006; Brereton et al., 2014) while the native shrubs used in this study are evergreen (Poole & Adams, 1994; Salmon, 1996; Metcalf, 2011). The process of leaf growth and senescence involves nutrient assimilation and mobilization that affects the nutritional components across the seasons (Brereton, 2014; Chapman, 2014; Kanojia et al., 2021).

The DM for *S. schwerinii* was unaffected by seasons. However, native shrub DM was higher in winter, lower in summer and showed inconsistencies in spring. The similar DM for *S. schwerinii* in spring and summer could have resulted because the foliage leaves sampled in the spring season were already expanded. However, the native shrubs higher DM in winter and lower in summer can be expected because of the warming and lengthening photoperiod during summer that leads to increased photosynthetic activity and cellular turgidity (Wardle, 1985; Tanaka et al., 2015; González-Zurdo, 2016).

A higher CP was observed in spring than summer for *S. schwerinii,* but the CP was unaffected across the seasons for most of the native shrubs. The higher CP for *S. schwerinii* in spring than summer has been reported previously (Oppong, 2002; Kemp, 2003) and resulted from the increased mobilization of nitrogen from perennating organs to the growing leaves during the spring season (Cooke & Weih, 2005; Weih, 2009; Brereton, 2014). However, leaf senescence in the native species due to aging result in mixed leaf age across seasons (González-Zurdo, 2016). The physiological process of senescing leaves in evergreen involves transfer of nitrogen from the old to new leaves (González-Zurdo, 2016), which can explain the invariable CP across the seasons for most native shrubs.

Although structural leaf cell wall content (ADF, NDF and lignin) varied across seasons for both *S. schwerinii* and native shrubs, the trend was different. Leaf structural cell wall content increased between spring and summer for *S. schwerinii* and would be expected because the juvenile leaves in spring matured and accumulated the structural cell wall contents in the summer season (González-Zurdo, 2016). However, native shrubs had higher ADF in winter and lower in spring and summer seasons, with an inverse trend observed for NDF. Increasing temperatures and photoperiod from spring through summer triggers new leaf growth which are lower in ADF and high in NDF with an inverse trend observed in winter (González-Zurdo, 2016). In addition, (González-Zurdo, 2016) showed that increased ADF and NDF is an adaptative response of evergreen plants to cold temperatures and short photoperiod in winter as was observed in this study. However, lignin was invariable across the seasons for all the native shrubs. Lignin is a major structural component maintaining leaf rigidity (González-Zurdo, 2016) and sampled leaves were of mixed age across the seasons. In both *S. schwerinii* and native species, ME was higher in spring than summer, which is expected because ME is inversely related to the structural cell wall contents (Waghorn, 2007).

Forages should contain CP above 7% DM for normal rumen microbial activity (Yang et al., 2018) and over 10% DM to meet ruminants maintenance requirements (Waghorn, 2004; Hynd, 2019). Within seasons, *S. schwerinii* leaf was superior in CP to the native shrubs during the spring but were similar in during the summer season. This implies that, *S. schwerinii* CP can meet ruminant maintenance requirement in spring and support microbial activity in summer. *Salix schwerinii* CP in summer in this study was similar to that reported by (Oppong, 2002; McWilliam, 2004) but lower than reported by (Douglas, 1996). Except *H. populnea,* all the other native shrubs CP was below the maintenance requirements for ruminants in all the seasons. In addition, *P. arboreus* CP was below the minimum required for rumen microbial activity in all seasons, *G. littoralis* in spring and summer and *P. crassifolium* in summer. The CP for native shrubs other than *H. populnea* was lower than for common pasture species (perennial ryegrass, red clover, plantain and chicory) in New Zealand (Kemp et al., 2014; Pain, 2015; Dalley et al., 2017; Litherland & Lambert, 2017) in all seasons. *Hoheria populnea* CP was lower than reported for Tagasaste, broom and black locust, within the range for tree medic, gorse and ceanothus and higher than for Manuka and Tauhinu (Lambert, 1989b).

Forage ADF and NDF are essential for rumen normal functioning and energy supply to ruminants (Pain, 2015; Beef+Lamb NZ, 2018a; Hynd, 2019). However, ADF and NDF lower than 20% DM and 30% DM and higher than 50% DM and 70% DM, respectively can compromise forage digestibly and utilization by ruminants (Waghorn, 2004; Hynd, 2019). The ADF and NDF for all shrubs were within the acceptable ranges for grazing animals except *P. arboreus* which was lower in all the seasons. Except for *P. arboreus,* the ADF and NDF of all shrubs were within the ranges reported for common pasture species (perennial ryegrass, red clover, plantain and chicory) (Kemp, 2014; Pain, 2015; Dalley, 2017; Litherland, 2017) and forage shrubs (Lambert, 1989b; Douglas, 1996; Vandermeulen, 2018) in New Zealand. The ADF and NDF for *P. arboreus* was within the ranges reported for fodder supplements (brassica, rape, swedes, beets, and turnips) used in New Zealand (De Ruiter et al., 2007; Guevara-Escobar et al., 2007; Dalley, 2017; Litherland, 2017).

Most native shrubs had superior ME to *S. schwerinii* in all the seasons and were within the ranges reported for fodder supplements (brassica, rape, swedes, beets, and turnips) (De Ruiter, 2007; Guevara-Escobar, 2007; Dalley, 2017; Litherland, 2017; Beef+Lamb NZ, 2018a) and higher than for common pasture species (Kemp, 2014; Pain, 2015; Litherland, 2017; Beef+Lamb NZ, 2018a) used in New Zealand. However, the ME for *H. populnea* and *S. schwerinii* were within the ranges reported for hill country pastures (McWilliam, 2005b; Guevara-Escobar, 2007; Pain, 2015; Beef+Lamb NZ, 2018a). *Salix schwerinii* ME in this study was higher than reported for *S. schwerinii* foliage (leaves plus stems < 5 mm diameter) in summer and lower than the average for willow and poplar foliage in spring and summer (Kemp, 2003).

4.4.2. Seasonal variation in stem nutritional composition

Stem nutritional composition was relatively stable but below the minimum requirements for rumen microbial activity (Yang, 2018). The CP was lower than for common pasture species and supplement fodder crops (Kemp, 2014; Pain, 2015; Litherland, 2017) but within the range reported for hay and straws (Dalley, 2017) in New Zealand. *Salix schwerinii* had similar range in ADF, NDF, lignin and ME in both the spring and summer seasons with all the native shrubs except for *P. arboreus*. However, the ADF, NDF, lignin for all the shrubs were comparable to summer pastures (Waghorn, 2004; Pitta, 2009) and lower than reported for forage shrubs (Lambert, 1989b) in New Zealand. Additionally, the ME for all shrubs was higher than reported for summer pastures (Pitta, 2007, 2009; Beef+Lamb NZ, 2018a).

The stem nutritional composition was more variable across the seasons for the native shrubs than for *S. schwerinii*. *Salix schwerinii* stems varied only in CP between spring and summer while the native shrubs had variable DM, ADF and NDF across the seasons. However, lignin was unaffected by seasons for both *S. schwerinii* and native shrubs. The decrease in CP for *S. schwerinii* between spring and summer could have resulted from the increased mobilization of nitrogen from the stem reserves to the growing foliage and catkins formation (Cooke, 2005; Brereton, 2014). However, variation in DM, ADF and NDF for the native shrubs can be associated with their phsiological response to seasonal changes in ambient conditions (González-Zurdo, 2016).

The low stem DM in spring and summer indicate native shrubs stem cells were more turgid and could have resulted from new growth due the increased photosynthetic activity with increasing temperature and photoperiod (Wardle, 1985; Tanaka, 2015; González-Zurdo, 2016). Further, the new stem growth for the native shrubs can explain the observed higher NDF in spring and summer and low in winter and an inverse for the ADF (González-Zurdo, 2016). Although there was new stem growth in spring and summer for all the shrubs, sampled stems contained woody portions explaining the invariable lignin across the seasons (González-Zurdo, 2016). Generally, stem ME for most of the shrub species was unaffected by the season and can be associated to the high structural cell wall content of the stems (Waghorn, 2007).

4.4.3. Comparison of Salix schwerinii and native shrubs as potential forage

Although climatic conditions in New Zealand can support year-round pastures production, the quantity and nutritional composition fluctuate with season (Waghorn, 2004). The nutritional composition of pasture in hill country sheep and beef cattle farms fluctuates more in summer on steep slopes because of soil moisture deficit and poor soil fertility (Kemp, 2016). Hill country pastures in summer have been shown to contain CP >10% DM (Dove, 2010; Litherland, 2017) but low in ME (<10 MJ/ kg DM) (Kemp, 2001; Oppong, 2001; Pitta, 2007, 2009; Nicol, 2017). Willows and poplar foliage contains higher ME than pastures in summer and are often used as supplementary fodder (Oppong, 2001; McWilliam, 2005b; Pitta, 2007). Comparison of *S. schwerinii* to native shrub has revealed that native shrubs leaves are superior in ME (>10 MJ/ kg DM) but stems nutritional composition are generally comparable. However, the native shrubs except *H. populnea* have lower CP than *S. schwerinii* in spring but are comparable in summer. Unlike other native shrubs, *H. populnea* was comparable to *S. schwerinii* in ME but was superior to *S. schwerinii* in CP during summer. In addition, native shrubs were lower in structural cell wall contents than *S. schwerinii* in summer suggesting they would be more digestible. Higher digestibility of native shrubs than *S. schwerinii* have been reported in Chapter 5. Comparison of *S. schwerinii* to native shrubs demonstrates that native shrubs can be potential sources of fodder to supplement the low ME found in pastures in summer. In addition, the native shrubs can provide herbage during winter because they are evergreen in contrast to *S. schwerinii*.

4.5. Conclusion

The finding from this study show that native shrubs leaves contain superior ME than *S. schwerinii* and pastures in summer. In addition, *S. schwerinii* and native shrub leaves and stem contain ADF and NDF within ranges acceptable for ruminants. However, the native shrubs with exception of *H. populnea* have lower CP than can meet the maintenance requirements of grazing animals in all seasons. Therefore, native shrubs can be used as potential supplementary fodder in winter when pasture quantity is low to provide herbage and during the summer when pastures quality is poor to provide ME. However, additional studies to determine native shrub intake and preference by sheep are recommended.

Forward to chapter 5

In Chapter 4, the nutritional composition of the edible leaf and stem of five native shrubs and an exotic osier willow was evaluated and compared within and across seasons. Chapter 5 focused on the spring season samples to compare the *in vitro* fermentation characteristics and digestibility of the shrubs.

Chapter 5: *In-Vitro* Fermentation of Browsable Native Shrubs in New Zealand

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Abstract

Information on the nutritive value and *in vitro* fermentation characteristics of native shrubs in New Zealand is scant. This is despite their potential as alternatives to exotic trees and shrubs for supplementary fodder, and their mitigation of greenhouse gases and soil erosion on hill-country sheep and beef farms. The objectives of this study were to measure the *in vitro* fermentation gas production, predict the parameters of the *in vitro* fermentation kinetics, and estimate the *in vitro* fermentation of volatile fatty acids (VFA), microbial biomass (MBM), and greenhouse gases of four native shrubs (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, and *Pittosporum crassifolium*) and an exotic fodder tree species, *Salix schwerinii*. The total *in vitro* gas production was higher ($p < 0.05$) for the natives than for the *S. schwerinii*. A prediction using the single-pool model resulted in biologically incorrect negative *in vitro* total gas production from the immediately soluble fraction of the native shrubs. However, the dual pool model better predicted the *in vitro* total gas production and was in alignment with the measured *in vitro* fermentation end products. The *in vitro* VFA and greenhouse gas production from the fermentation of leaf and stem material was higher ($p < 0.05$), and the MBM lower ($p < 0.05$), for the native shrubs compared to the *S. schwerinii*. The lower *in vitro* total gas production, VFA, and greenhouse gas production and higher MBM of the *S. schwerinii* may be explained by the presence of condensed tannins, although this was not measured and requires further study. In conclusion, the results from this study suggest that when consumed by ruminant livestock, browsable native shrubs can provide adequate energy and microbial protein, and that greenhouse-gas production from these species is within the ranges reported for typical New Zealand pastures.

Keywords: native shrubs; *in vitro* fermentation; volatile fatty acids; greenhouse gases; hill country

5.1. Introduction

Sheep are efficient utilizers of pastures due to the symbiotic anaerobic microbiota, which mainly comprises the bacteria, archea, fungi, and protozoa in their reticulorumen (Pitt et al., 1999; Cholewińska et al., 2020; McLoughlin et al., 2020). These microorganisms obtain nutrients by fermentatively breaking down the ingested feed, and providing organic acids, microbial proteins, and some B complex vitamins to the host in return (Owens & Mehmet, 2016). These fermentation processes also produce gases, primarily carbon dioxide and methane, which are major greenhouse gases (Owens, 2016). Organic acids, principally acetic, propionic, and butyric volatile fatty acids (VFA) supply 70 to 80% of the dietary energy (Owens, 2016) of ruminants, while microbial protein provides 70 to 100% of the amino acids they require (Uddin et al., 2015). However, diet influences the reticulorumen microbial profile, which determines the rate of substrate fermentation and VFA and gas composition (Dewhurst et al., 2000; Ramos et al., 2009; Owens, 2016). Fibrous diets are slow to degrade and encourage acetogenic anaerobes and methane-gas production, while diets rich in simple carbohydrates are highly fermentable and promote mainly propiogenic microbes and carbon-dioxide-gas production (Dewhurst, 2000; Ramos, 2009).

Both *in vivo* and *in vitro* methods can be used to evaluate feed substrates' digestibility and their nutritive value, but *in vitro* methods are mainly because they are convenient and inexpensive proxies for *in vivo* fermentation (Pitt, 1999; Rivero et al., 2020). *In vitro* methods involve the incubation of feed substrate in buffered rumen fluid with measurement of gas production periodically, and VFA and residue at the end of the fermentation process (Tedeschi et al., 2008; Owens, 2016). Unlike *in vivo* methods, in which VFAs are absorbed across the rumen wall, VFAs accumulate in rumen fluids in vitro, and their concentration indicates the actual production from the substrate (Owens, 2016). Similar to *in vivo* methods, the residue obtained after the fermentation process can be used to determine the substrate digestibility and the microbial protein utilizable by the host (Dewhurst, 2000).

Gas produced *in vitro* correlates with the rate of substrate fermentation and can be fitted to mathematical functions to estimate feed-substrate fermentation kinetic parameters (Schofield et al., 1994; Pitt, 1999; López et al., 2007). Non-linear mathematical functions, mainly exponential and sigmoidal, are preferred because of their ability to model microbial growth and the fact that their parameters can be biologically explained (Schofield, 1994; Wang et al., 2011; Luiz et al., 2019). However, the suitability of the mathematical function for the estimation of the fermentation kinetic parameters depends on the nutritive composition of the feed substrate (Pitt, 1999; Wang, 2011; Assis et al., 2021). Single-compartment models, also referred to as single-pool functions, assume a constant rate of fermentation and are mainly suited to feed substrates with homogenous nutrients, while dual-pool functions consider two rates of fermentation and are suitable for feed substrates with heterogenous nutrients (Schofield, 1994; Wang, 2011; Luiz, 2019; Assis, 2021). The application of both single- and dual-pool non-linear functions is common in feed evaluation because natural feeds consumed by sheep contain a mixture of substrates that vary in nutrient composition (Schofield, 1994).

Pasture, predominantly perennial ryegrass with a small proportion of clover, is the cheapest and most widely utilized feed resource in hill-country sheep and beef farms in New Zealand (Campbell, 1973; Morris, 2014; Webby, 2017). In addition, supplementary feeds are used during seasons with low pasture supply and quality (De Ruiter, 2007; Webby, 2017). The supplementary feeds that can be used on hill-country sheep and beef farms include conserved forages, alternative grazed forages, and concentrates (De Ruiter, 2007). Further, the foliage harvested from poplar and willow trees, commonly used for soil conservation on hill-country sheep and beef farms, can be used as a source of supplementary forage during the summer season (Kemp, 2003; McWilliam, 2005a; Taranaki Regional Council, 2016). Native shrubs may also offer potential feed sources when browsed *in situ* (Nugent, 1990; Forsyth, 2002; Dickinson, 2015), but this has not yet been widely explored (Dickinson, 2015) (Chapter 3).

In New Zealand, native shrubs offer cultural value, genetic diversity, adaptability, and soil conservation, and they are evergreen and can supply foliage throughout the year (Bergin, 2014b; Dickinson, 2015). Some native shrubs species are strongly preferred by wild herbivores, suggesting their potential as livestock-feed resources (Mitchell, 1987; Nugent, 1990; Forsyth, 2002). However, their nutritive value, *in vitro* fermentation gas production, fermentation kinetics, and fermentation end products in domesticated ruminants have not been previously studied. Information on the nutritive value, *in vitro* fermentation gas production, fermentation kinetics, and fermentation end products of New Zealand native shrubs could be used for comparison with conventional feed resources, which would aid in decision making by policy makers, researchers, and hill-country farmers. The objective of this study was therefore to determine the *in vitro* fermentation gas production, fermentation kinetics, and fermentation end products of four New Zealand native shrubs with potential use as sheep fodder in comparison to an exotic shrub utilized on North Island hill-country sheep and beef farms.

5.2. Materials and Methods

5.2.1. Shrubs and study site description

All the shrubs used in Chapter 4 were used in this Chapter except *Pseudopanax arboreus* due to insufficient sample quantity. Only the spring season samples were used due to insufficient sample quantity for winter and summer seasons. The shrubs are described in Chapter 4 section 4.2.1. and the study site in section 4.2.2.

5.2.2. Sample collection and processing

Foliage samples, consisting of leaved stems with a diameter of less than 5 mm, were collected in October 2020. Five shrubs in each plot were randomly selected and at least five foliage samples harvested from each shrub. A total of 20 foliage samples were collected, comprising five shrub species, in each of the four blocks. The foliage samples were indiscriminately harvested from the lower, middle, and top parts (not higher than 1.1 m) of the shrub to imitate the browsing behavior of sheep and to ensure the samples were representative of the entire shrub. Foliage samples for each shrub species from each plot were pooled, labeled, and chilled to approximately 4°C while being processed. Any foreign materials, such as grass, dead leaves, and spider webs were removed from the collected samples (n = 20, i.e., five species by four pooled samples), before further separating the foliage samples into leaf (n = 20) and stem (n = 20) sub-samples. The leaf sub-sample included the leaf blade, stipules, buds, and petiole. The stem sub-sample included the woody and soft bark to which the leaves were attached. The sub-samples were frozen before submission to the Massey University Food and Nutrition Laboratory for freeze drying, grinding and proximate analysis of nutrients. A portion of the ground sub-samples (20 leaf and 20 stems; n = 40) was submitted to Alltech laboratories, Auckland, for *in vitro* fermentation analysis.

5.2.3. Proximate analysis and in vitro digestibility

The proximate nutritional composition analysis for the shrubs has been described in Chapter 4 section 4.2.5.

5.2.4. Measuring in vitro fermentation gas production

In vitro fermentation was carried out using the Alltech IFM™ (Alltech, New Zealand) to determine fermentation gas production, VFA, and microbial biomass (MBM). The procedure used is described by Jack (2020). Each sub-sample (20 leaf and 20 stems; $n = 40$) was duplicated into 0.5-gram portions to be incubated in an *in vitro* medium made up of a mixture of rumen-fluid inoculum and buffer solution. Rumen fluid was collected from a fistulated lactating dairy cow in the morning approximately two hours after *ad lib* feeding on pasture and supplemented with grass and maize silage, 0.5 kg of molasses, and 1.5 kg pelleted dairy concentrate. The freshly collected rumen fluid was filtered through a double layer of cheese cloth to remove undigested material and was mixed with 5.6 L of McDougall bicarbonate buffer solution (McDougall, 1948) and 250 mL of a reducing agent to make an *in vitro* medium with a 20:80 rumen fluid-to-buffer ratio. Each sub-sample portion was added into 100 mL of *in vitro* medium in 250-milliliter bottles and incubated at 39°C for 48 h with gentle stirring and periodic pH checks (Mould et al., 2005). Fermentation gas production was measured using an automated-pressure transducer and recorded continuously for 48 h (Pell & Schofield, 1993). The recorded gas production was used to estimate the *in vitro* fermentation kinetics for the shrub species.

5.2.5. Estimating the in vitro fermentation kinetics parameters

Nonlinear mathematical models are widely used to fit *in vitro* gas production to describe the fermentation kinetics of ruminant feeds (Assis, 2021). The nonlinear models vary in structure, parameters, time zero behavior, lag period, points of inflection, and fermentation gas pools (Pitt, 1999; Assis, 2021). Descriptions of some nonlinear models commonly used to fit *in vitro* gas production can be found in Schofield (1994); Pitt (1999); Wang (2011) and Assis (2021). However, the exponential and sigmoidal models are preferred because they are robust in relating gas production to microbial mass and substrate levels (Schofield, 1994) and can be structured to accommodate more than one fermentation gas pool (Assis, 2021). Single-pool models are better predictors of fermentation kinetics of simple substrates and are suggested for feeds with low fiber, while multipool models are better descriptors of heterogenous substrate and consider each substrate fraction independently, and they are recommended for feeds with high fiber (Assis, 2021). Combined use of single and multipool models has been suggested when determining the best model to describe fermentation kinetics, where substrate fractions in the test feeds are unknown (Assis, 2021). Exponential single-pool (Orskov & Mcdonald,

1979) (Equation 111) and logistic dual-pool (Schofield, 1994) (Equation 12) models are extensively used and validated in fitting *in vitro* fermentation gas production (Getachew et al., 1998; Wang, 2011) and were selected to describe the *in vitro* fermentation kinetics of the study shrub species.

Measured gas production for each sub-sample was combined for each shrub species and fitted using SAS non-linear procedure (Proc NLIN) (SAS software version 9.4 (SAS Institute, Cary, NC, USA)) to estimate model parameters that describe the rates and volumes of gas production from the sub-samples at given time (t) in hours. In the single-pool model, total gas production (V_{Ors}) in milliliters per gram of dry matter (mL/g DM) was the sum of gas production from the highly (a, mL/g DM) and slowly (b, mL/g DM) fermentable nutrients, produced at similar fermentation rates (c), expressed in percentage gas production per hour (%/h). Total gas production in the dual-pool model ($\mathrm{V_{Sch}}$, mL/g DM) was the sum of gas production from the fast pool (V_1, mL/g DM) portion and the slow pool (V_2, mL/g DM) produced from the highly fermentable and slowly fermentable substrate fractions, respectively. The V_1 and V_2 were assumed to have similar lag (L) times, but the rates of gas production (C_1, %/h) for V_1 and (C_2, %/h) for V_2 were different.

Equation 11 $$V_{Ors} = a + b(1 - e^{-ct})$$

Equation 12 $$V_{Sch} = \left[\left(V_1/\left(1 + \mathrm{e}^{(2+4\times C_1(\mathrm{L}-\mathrm{t}))}\right)\right) + \left(V_2/\left(1 + \mathrm{e}^{(2+4\times C_2(\mathrm{L}-\mathrm{t}))}\right)\right)\right]$$

Shrub total gas production after 24 h for the single pool (V_{24}, mL/g DM) and dual pool ($V_{1_{24}}$ and $V_{2_{24}}$, mL/g DM) was determined at $t = 24$ h for both models. The gas production half-life was assumed to be time (t, h) at which half of the total gas for each pool was produced (Wang, 2011). Gas production half-life was estimated using the t function of the (Orskov, 1979) ($T_{0.5}$, h) (Equation 13) and (Schofield, 1994) ($V_{T_{0.5}}$, h) (Equation 14) models.

Equation 13 $$T_{0.5} = -\left(\ln\left(-{}^{0.5V_{Ors}}/_{b}\right) + \left({}^{a}/_{b}\right) + 1\right)/c$$

Equation 14 $$V_{T_{0.5}} = -(\ln(-0.5)/4\mathrm{c}) + \mathrm{L} + (1/2\mathrm{c})$$

where $V_{T_{0.5}}$ was $V_{1_{T0.5}}$ or $V_{2_{T0.5}}$

Model performance was determined by regressing predicted (x-axis) against observed (y-axis) gas production over 48 h (Gauch et al., 2003; Piñeiro et al., 2008; Wang, 2011; St-Pierre, 2016). Regression residuals were used to determine the model's goodness of fit and accuracy using root mean square error (RMSE) and mean absolute percentage error (MAPE) metrics (Richter et al., 2011; Swanson, 2015). Since RMSE units were similar to the regressed variables, low RMSE indicated high fitness of the models (Richter, 2011). A MAPE lower than 5% showed excellent, 10 to 25% good, and greater than 25% very low and unacceptable model-prediction accuracy (Swanson, 2015). Adjusted coefficient of determination (adjusted R^2) was used to indicate the proportion of variability explained by the models, with values close to one suggesting a stronger relationship between the predicted and observed gas-production values (Richter, 2011).

5.2.6. *In vitro fermentation end products*

After 48 h of *in vitro* fermentation, the medium pH was measured before centrifuging. The supernatant was used to determine the VFA concentration, and the residues were used to estimate the sub-sample’s digestibility and the MBM. Volatile fatty acids (acetate, propionate, butyrate and valerate) and their isomers (isobutyrate and isovalerate) were recovered using the method suggested by Erwin et al. (1961), and their concentration was determined using the Agilent GC 7890 (Flame Ionization Detector, FID) gas chromatography system. Total VFAs were expressed in millimolar (mM) concentration produced per gram of dry matter (g DM) incubated while individual VFA and their isomers were expressed as the percentage of the total VFA. The concentration of individual VFA was used to balance theoretical fermentation Equations to predict the volume (mL) and mass (g) of carbon dioxide (CO_2) and methane (CH_4) gases produced per g DM during the sub-samples fermentation (Wolin, 1960). Predicted fermentation gas proportions were pooled using their global-warming potential (Ledgard & Falconer, 2015) to determine the CO_2 equivalent (Eq CO_2) emission potential of the shrub samples per g DM. The residue (undegraded sub-samples containing MBM) weight was used to determine the apparent digested DM (aDMD) (Tilley & Terry, 1963), while the weight after solubilization of the MBM was used to estimate the true digested DM (DMD) (Goering & Van Soest, 1975) as a percentage of the DM (% DM). The MBM (mg/g DM) yield was estimated as the difference between aDMD and DMD weights (Goering, 1975). In addition, the results of total VFA, MBM, and greenhouse gases were divided by the corresponding digested dry matter to estimate the *in vitro* fermentation end products in terms of DDM (supplementary material, Tables 1 and 2). However, only the results in g DM are discussed because estimation of forage production, nutritional composition, and intake in ruminants are mainly in terms of DM.

5.2.7. Statistical Analysis

SAS software version 9.4 (SAS Institute, Cary, NC, USA) was used to carry out the statistical analysis. Analysis of variance in the general linear-model procedure (proc GLM) was used to compare the differences between the shrub samples' means for the leaves and stems for the proximate nutrients and *in vitro* fermentation end products. The means were considered different if $p > 0.05$ and were separated using the Tukey method.

5.3. Results

5.3.1. Shrubs nutritional composition

The proximate nutritional composition of both the leaves and the stems differed ($p < 0.05$) between the shrub species, except for the NDF content in the leaves ($p > 0.05$) (Table 15). The leaf DM was similar ($p > 0.05$) in both the *P. crassifolium* and the *S. schwerinii*, where it was higher ($p < 0.05$) than in all the other species. The ash content was higher ($p < 0.05$) in the *H. populnea* and lower ($p < 0.05$) in the *S. schwerinii* leaves than in all the other species. The CP was similar ($p > 0.05$) in the *H. populnea* and *S. schwerinii* leaves, and higher ($p < 0.05$) than all the other species, which did not differ ($p > 0.05$). The *Salix schwerinii* leaves had higher ($p < 0.05$) ADF than the *H. populnea* and *P. crassifolium*, which were similar ($p > 0.05$), while the *C. robusta* and *G. littoralis* did not differ ($p > 0.05$) from the other species. The lignin was higher ($p < 0.05$) in the *G. littoralis* and lower ($p < 0.05$) in the *S. schwerinii* and *H. populnea*, while the *C. robusta* and *P. crassifolium* were intermediate and did not differ ($p > 0.05$) from the other species.

The *Salix schwerinii* and *P. crassifolium* had similar ($p > 0.05$) stem DM, which was higher ($p < 0.05$) than in the other species. The *Hoheria populnea* had higher ($p < 0.05$) and the *S. schwerinii* had lower ($p < 0.05$) stem ash than all other species. The stem CP was similar ($p > 0.05$) in the *H. populnea* and *S. schwerinii*, where it was higher ($p < 0.05$) than in the other species, which were not different ($p > 0.05$). The stem ADF and NDF were higher ($p < 0.05$) in the *H. populnea* and lower ($p < 0.05$) in the C. *robusta*, compared to the other species. Unlike in the leaves, the *S. schwerinii* had higher ($p < 0.05$) stem lignin content than all the other species, except the *G. littoralis*, which was comparable ($p > 0.05$) to the other species.

Table 15. Native (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, and *Pittosporum crassifolium*) and exotic (*Salix schwerinii*) shrub species leaf ($n = 20$) and stem ($n = 20$) dry matter (DM, %) as a percentage of the fresh weight, and ash (Ash, %), crude protein (CP, %), neutral detergent fibre (NDF, %), acid detergent fibre (ADF, %), lignin (Lignin, %), *in vitro* dry-matter digestibility (IVDMD, %), *in vitro* digestible organic content in dry matter (IVDOMD, %), *in vitro* organic-matter digestibility (IVOMD, %) as percentages of the DM and metabolizable energy (ME, MJ/kg DM).

Shrub Species	DM	Ash	CP	NDF	ADF	Lignin	IV DMD	IV OMD	IV DOMD	ME
					Leaf					
Coprosma robusta	39.3^{b}	7.0^{bc}	7.9^{b}	37.4	22.4^{ab}	9.6^{ab}	78.8^{a}	82.3^{a}	75.0^{a}	12.0^{a}
Griselinia littoralis	31.5^{c}	7.3^{b}	6.2^{b}	32.1	22.3^{ab}	12.0^{a}	78.6^{a}	82.0^{a}	74.6^{a}	11.9^{a}
Hoheria populnea	31.1^{c}	11.6^{a}	14.0^{a}	37.6	20.2^{b}	7.5^{b}	77.4^{a}	80.1^{b}	71.2^{b}	11.4^{b}
Pittosporum crassifolium	43.0^{a}	6.5^{c}	6.2^{b}	36.4	20.7^{b}	9.3^{ab}	78.4^{a}	81.8^{ab}	74.7^{a}	12.0^{a}
Salix schwerinii	43.1^{a}	4.9^{d}	15.1^{a}	36.3	24.6^{a}	8.8^{b}	73.7^{b}	76.5^{c}	70.4^{b}	11.3^{b}
Pooled SE	0.57	0.17	0.41	1.31	0.63	0.62	0.32	0.40	0.42	0.07
					Stem					
Coprosma robusta	35.8^{b}	6.4^{bc}	4.7^{b}	46.6^{c}	36.7^{b}	9.1^{b}	67.8	69.9^{a}	63.7^{a}	10.2^{a}
Griselinia littoralis	32.1^{b}	5.6^{c}	4.2^{b}	48.6^{bc}	38.6^{ab}	10.2^{ab}	66.3	68.4^{ab}	62.5^{ab}	10.0^{ab}
Hoheria populnea	36.0^{b}	9.0^{a}	8.3^{a}	53.5^{a}	41.5^{a}	9.2^{b}	65.2	66.5^{ab}	60.0^{b}	9.6^{b}
Pittosporum crassifolium	47.4^{a}	6.7^{b}	4.2^{b}	52.0^{ab}	41.0^{ab}	8.8^{b}	64.2	65.9^{b}	60.0^{b}	9.6^{b}
Salix schwerinii	48.5^{a}	3.7^{d}	7.0^{a}	48.9^{bc}	38.4^{ab}	11.6^{a}	66.9	69.4^{ab}	63.9^{a}	10.2^{a}
Pooled SE	1.05	0.23	0.37	0.95	1.07	0.38	0.87	0.91	0.82	0.13

Values with different superscripts in leaf and stem columns are different at $p < 0.05$.

The leaves' IVDMD was similar ($p > 0.05$) and higher ($p < 0.05$) for the native shrubs than for the *S. schwerinii*. *Salix schwerinii* leaves had lower ($p < 0.05$) IVOMD than the native shrubs (Table 3). However, the IVDOMD and ME were similar ($p > 0.05$) for the *H. populnea* and *S. schwerinii* leaves and lower ($p < 0.05$) than the other shrubs, which did not differ ($p > 0.05$). There were no differences ($p > 0.05$) in stem IVDMD between the species. However, the *C. robusta* had higher and *P. crassifolium* had lower stem IVOMD than the other shrubs, which did not differ from any other shrub. The stem IVDOMD and ME were similar ($p > 0.05$) for C. *robusta* and *S. schwerinii*, and higher ($p < 0.05$) than for the other species, except for *G. littoralis*, which was not different ($p > 0.05$) from any of the other shrubs.

5.3.2. Shrubs In vitro Gas Production

The total gas production from *in vitro* fermentation for the leaf and stem differed ($p < 0.05$) between the species (Table 16). For both leaf and stem material, the *S. schwerinii* had lower ($p < 0.05$) gas production compared to the native shrub species. The gas production from the leaves was similar ($p > 0.05$) to that of the stem for *H. populnea* and *S. schwerinii*, but for the other species, the gas production was higher ($p < 0.05$) for the leaves than for the stems.

Table 16. Total gas production (mL/g DM) from the *in vitro* fermentation of leaf ($n = 20$) and stem ($n = 20$) material from native (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, and *Pittosporum crassifolium*) and exotic (*Salix schwerinii*) shrub species.

Species	Leaf	Stem	SE
Coprosma robusta	157.0^{a}	$105.9^{a\dagger}$	6.92
Griselinia littoralis	151.7^{ab}	$105.9^{a\dagger}$	5.01
Hoheria populnea	116.6^{b}	108.6^{a}	7.01
Pittosporum crassifolium	135.3^{ab}	$100.8^{a\dagger}$	8.80
Salix schwerinii	46.1^{c}	68.6^{b}	6.58
SE	8.42	5.12	

^{abc} Mean total gas production for the shrubs in columns with different-letter superscripts differ significantly at $p < 0.05$. † Mean total gas production of leaves and stems in rows with symbol superscripts differ significantly at $p < 0.05$.

5.3.3. Shrubs In vitro Fermentation Kinetics

The parameter estimates of the *in vitro* fermentation kinetics for the shrub leaves using the single-pool model are shown in Table 17, and the resulting gas-production curves are presented in Figure 22. The function parameters for the immediately soluble fraction (a, mL/g DM) were negative for the native shrubs. The gas production from the slowly degradable fraction (b, ml/g DM) and the total gas production (V_{ors}, mL/g DM)) were more than three times higher in the native shrubs than in the *S. schwerinii*. However, the *H. populnea* had a slower rate of gas production (c, %/h) than all the other species, resulting in lower gas production after 24 h (V_{24}, mL/g DM) and the longest gas production half-life ($T_{0.5}$, h). The native shrub species had better model performance for the leaves than the *S. schwerinii*, which had very low accuracy (MAPE = 21.54) and a weak relationship (adjusted $R^2 = 0.414$) between the observed and predicted gas production.

The parameter estimates for the stem *in vitro* fermentation kinetics (Table 18 and Figure 22) were negative, except in the *C. robusta* and *S. schwerinii*. The b and V_{ors} parameters were higher in the natives than in the *S. schwerinii*. However, the *C. robusta* and *S. schwerinii* had lower c, resulting in lower V_{24} compared to the other shrub species. In contrast to the leaf model, the model for the *S. schwerinii* stems had the best fit (RMSE = 4.25) and explained a larger proportion of the variability (adjusted $R^2 = 0.935$) between the predicted and observed gas production compared to the native shrub species and had a high mean absolute percentage error (MAPE = 3.14).

Table 17. Native (*Coprosma robusta, Griselinia littoralis, Hoheria populnea*, and *Pittosporum crassifolium*) and exotic (*Salix schwerinii*) shrub species leaf *in vitro* fermentation kinetic parameters derived using single pool model, where: *a*, gas production from immediately soluble fraction (mL/g DM); *b*, gas production from slowly degradable fraction (mL/g DM); *c*, rate of gas production (%/h); V_{Ors}, total gas production (mL/g DM); V_{24}, total gas production after 24 h (mL/g DM); and $t_{0.5,}$ half-life of total gas production (h).

Species	Parameters	*a*	*b*	*c*	V_{ors}	V_{24}	$t_{0.5}$	MAPE	RMSE	Adj R^2
Coprosma robusta	Value	−1.0	165.3	0.070	164.3	133.1	10.2	−0.59	11.48	0.932
	SE	0.99	0.93	0.001						
	Lower 95% CI limit	−3.0	163.5	0.067						
	Upper 95% CI limit	0.9	167.1	0.072						
Griselinia littoralis	Value	−6.9	166.6	0.079	159.7	134.5	9.9	2.18	5.69	0.983
	SE	0.51	0.47	0.001						
	Lower 95% CI limit	−7.9	165.7	0.078						
	Upper 95% CI limit	−5.9	167.5	0.08						
Hoheria populnea	Value	−3.5	139.7	0.043	136.2	85.9	17.5	−1.65	11.86	0.892
	SE	0.91	1.44	0.001						
	Lower 95% CI limit	−5.3	136.8	0.040						
	Upper 95% CI limit	−1.7	142.5	0.045						
Pittosporum crassifolium	Value	−4.4	146.7	0.091	142.3	125.9	8.3	2.56	16.17	0.840
	SE	1.53	1.41	0.002						
	Lower 95% CI limit	−7.4	143.9	0.087						
	Upper 95% CI limit	−1.4	149.5	0.096						
Salix schwerinii	Value	2.4	43.2	0.064	45.6	36.3	9.2	−21.54	13.25	0.414
	SE	1.12	1.08	0.005						
	Lower 95% CI limit	0.2	41.1	0.054						
	Upper 95% CI limit	4.6	45.3	0.073						

RMSE, root mean square error. MAPE, mean absolute percentage error. Adj R^2, adjusted R squared.

Table 18. Native (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, and *Pittosporum crassifolium*) and exotic (*Salix schwerinii*) shrub species stem *in vitro* fermentation kinetic parameters derived using single-pool model, where: *a*, gas production from the immediately soluble fraction (mL/g DM); *b*, gas production from the slowly degradable fraction (mL/g DM); *c*, rate of gas production (%/h); V_{Ors}, total gas production (mL/g DM); V_{24}, total gas production after 24 h (mL/g DM); and $t_{0.5}$, half-life of total gas production (h).

Species	Parameters	a	b	c	Vors	V24	T0.5	MAPE	RMSE	Adj R2
Coprosma robusta	Value	4.9	104	0.055	108.9	81.2	11.0	−2.46	7.22	0.931
	SE	0.59	0.63	0.001						
	Lower 95% CI limit	3.7	102.7	0.053						
	Upper 95% CI limit	6.0	105.2	0.057						
Griselinia littoralis	Value	−4.5	115	0.09	110.5	97.3	8.6	−0.07	10.94	0.876
	SE	1.03	0.95	0.002						
	Lower 95% CI limit	−6.5	113.1	0.087						
	Upper 95% CI limit	−2.5	116.8	0.094						
Hoheria populnea	Value	−4.1	113.7	0.082	109.6	93.7	9.4	−0.18	11.01	0.875
	SE	1.0	0.92	0.002						
	Lower 95% CI limit	−6.1	111.9	0.079						
	Upper 95% CI limit	−2.1	115.5	0.085						
Pittosporum crassifolium	Value	−2.0	100.1	0.14	98.1	94.7	5.2	0.16	6.78	0.920
	SE	0.75	0.73	0.002						
	Lower 95% CI limit	−3.5	98.7	0.137						
	Upper 95% CI limit	−0.5	101.5	0.144						
Salix schwerinii	Value	5.6	62.9	0.057	68.5	52.4	9.3	3.14	4.25	0.935
	SE	0.35	0.36	0.001						
	Lower 95% CI limit	4.9	62.2	0.055						
	Upper 95% CI limit	6.3	63.6	0.059						

RMSE, root mean square error. MAPE, mean absolute percentage error. Adj R2, adjusted R squared.

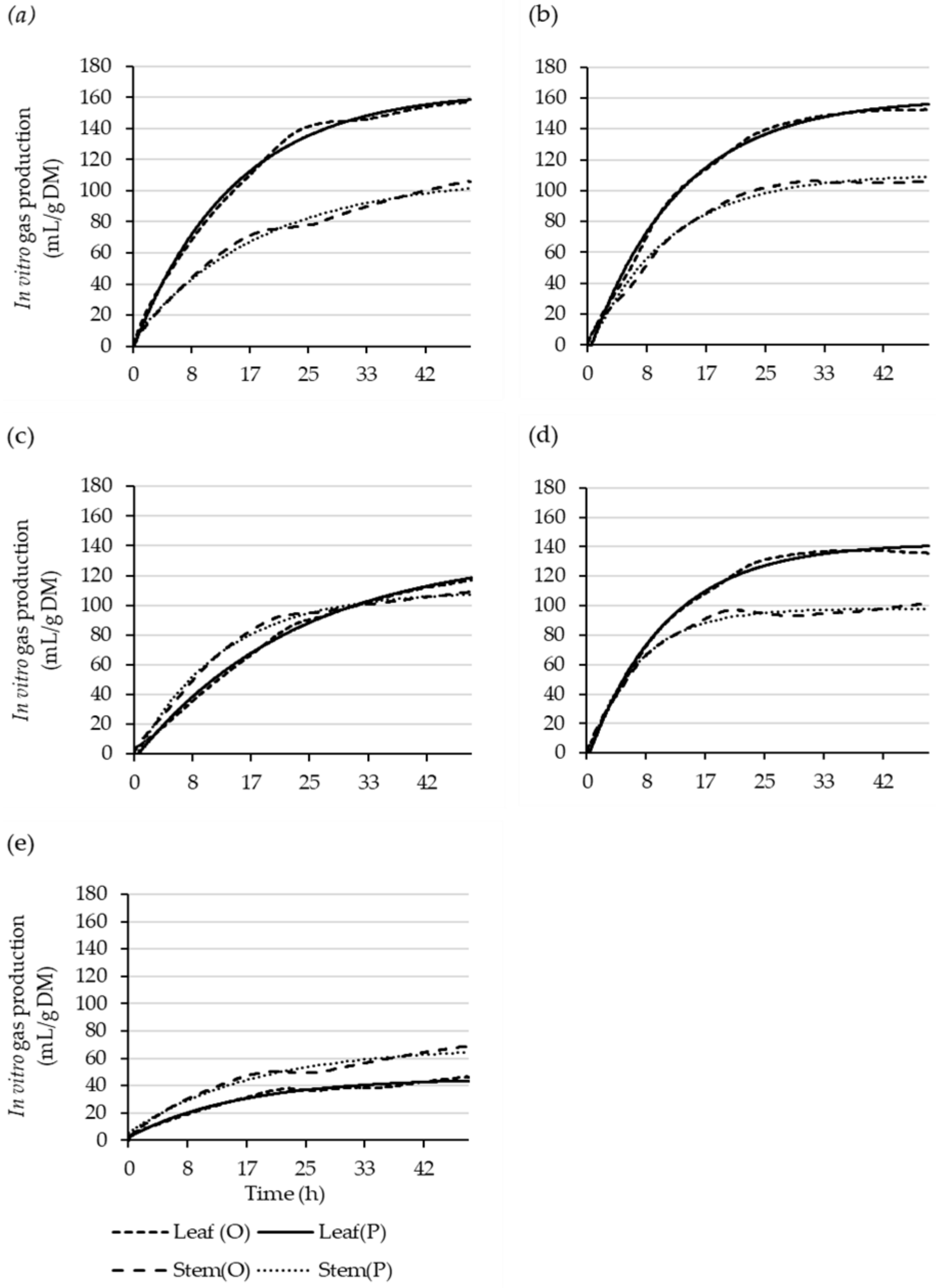

Figure 22. Observed (O) and single-pool-model-predicted (P) leaf and stem cumulative gas-production curves over 48 h for *Coprosma robusta* (**a**), *Griselinia littoralis* (**b**), *Hoheria populnea* (**c**), *Pittosporum crassifolium* (**d**), and *Salix schwerinii* (**e**).

The dual-pool-model *in vitro* fermentation kinetic parameter estimates for the leaves and stems are shown in Tables 19 and 20, and the resulting predicted gas-production curves are presented in Figures 23. The predicted leaf gas production from the fast pool (V_1, mL/g DM) was more than three times higher in the native shrub species compared to the *S. schwerinii*. However, the *S. schwerinii* had the highest rate of gas production for the fast pool (R_1, %/hr), resulting in a shorter gas-production half-life ($V_{1_{T_{0.5}}}$, h) compared to the native shrub species. The lag time (L, h) was shortest in the *S. schwerinii* and longest in the *H. populnea*. The gas production from the slow pool (V_2, mL/g DM) was higher in the natives compared to the *S. schwerinii*, except in the *C. robusta*. Unlike in the V_1, the *S. schwerinii* had the lowest rate of gas production for the slow pool (R_2, %/h), resulting in more than four times longer slow-pool gas-production half-life ($V_{2_{T_{0.5}}}$, h) compared to the native shrub species. The gas production after 24 h ($V_{1_{24}}$ and $V_{2_{24}}$, mL/g DM) was more than three times higher in the native shrub species compared to the *S. schwerinii*. Similarly, the performance of the dual -pool model was better for the native shrub species compared to the *S. schwerinii*, which had very low accuracy (MAPE = 22.42), and the relationship between the observed and predicted gas production was weaker (adjusted R^2 = 0.417).

Stem V_1 was lowest in the *H. populnea* compared to the other species. *Salix schwerinii* had the lowest R_1 but the shortest $V_{1_{T_{0.5}}}$. Stem L was highest for the *C. robusta*, followed by the *S. schwerinii*, and lowest for the *P. crassifolium*. The *Hoheria populnea* had the highest V_2, followed by the *G. littoralis*, while the other species were similarly lower. The *Pittosporum crassifolium* had the highest R_2 , resulting in the shortest $V_{2_{T_{0.5}}}$ compared to the *S. schwerinii*, which had more than four times longer $V_{2_{T_{0.5}}}$. The dual-pool model for the *S. schwerinii* stems had the best fit (RMSE = 3.71) and explained a larger proportion of the variability (adjusted R^2 = 0.950) between the predicted and observed gas production compared to the native shrub species and had a relatively good MAPE (−0.409).

Table 19. Native (*Coprosma robusta, Griselinia littoralis, Hoheria populnea*, and *Pittosporum crassifolium*) and exotic (*Salix schwerinii*) shrub species leaf *in vitro* fermentation kinetic parameters derived using dual-pool model, where: L, lag time (h); V_1, fast-pool total gas production (mL/g DM); V_2, slow pool (mL/g DM); R_1, fast-pool rate of gas production (%/h); R_2, slow rate (%/h); V_{Sch}, total gas production (mL/g DM); $V_{1_{24}}$, total gas production for the fast pool after 24 h (mL/g DM); $V_{2_{24}}$ slow pool after 24 h (mL/g DM); $V_{1_{T_{0.5}}}$, fast-pool total-gas-production half-life (h); and $V_{2_{T_{0.5}}}$, slow-pool half-life (h).

Species	Parameters	V_1	R_1	L	V_2	R_2	V_{Sch}	$V_{1_{24}}$	$V_{1_{T_{0.5}}}$	$V_{2_{24}}$	$V_{2_{T_{0.5}}}$	MAPE	RMSE	Adj R^2
Coprosma robusta	Value	120.3	0.043	1.36	33.02	0.191	153.3	104.3	12.3	33.0	5.4	−8.29	11.32	0.934
	SE	1.86	0.001	0.18	1.94	0.019								
	Lower CI	116.7	0.042	1.01	29.2	0.154								
	Upper 95% CI limit	124.0	0.044	1.71	36.8	0.228								
Griselinia littoralis	Value	92.2	0.040	1.84	60.8	0.123	153.0	75.8	13.6	60.8	6.9	−3.66	5.31	0.985
	SE	1.43	0.001	0.07	1.54	0.004								
	Lower 95% CI limit	89.4	0.039	1.69	57.8	0.116								
	Upper 95% CI limit	95.0	0.041	1.98	63.8	0.130								
Hoheria populnea	Value	70.5	0.025	2.67	50.2	0.069	120.7	38.2	21.0	49.2	10.3	−8.76	11.83	0.892
	SE	3.82	0.002	0.27	5.05	0.005								
	Lower 95% CI limit	63.0	0.022	2.15	40.3	0.059								
	Upper 95% CI limit	78.0	0.029	3.2	60.1	0.080								
Pittosporum crassifolium	Value	91.2	0.046	1.41	46.7	0.167	137.9	81.9	11.7	46.7	5.7	−5.53	16.08	0.842
	SE	3.43	0.002	0.23	3.6	0.019								
	Lower 95% CI limit	84.4	0.043	0.96	39.7	0.130								
	Upper 95% CI limit	97.9	0.049	1.86	53.8	0.204								
Salix schwerinii	Value	27.6	0.066	1.01	34.6	0.011	62.2	27.1	8.7	9.2	46.3	−22.42	13.21	0.417
	SE	3.62	0.013	2.2	26.37	0.005								
	Lower 95% CI limit	20.5	0.042	−3.31	−17.1	0.000								
	Upper 95% CI limit	34.7	0.091	5.34	86.4	0.021								

Table 20. Native (*Coprosma robusta, Griselinia littoralis, Hoheria populnea*, and *Pittosporum crassifolium*) and exotic (*Salix schwerinii*) shrub species leaf *in vitro* fermentation kinetic parameters derived using dual pool model, where, L, lag time (h); V_1, fast-pool total gas production (mL/g DM); V_2, slow pool (mL/g DM); R_1, fast-pool rate of gas production (%/h); R_2, slow rate (%/h); $\mathrm{V}_{\mathrm{Sch}}$, total gas production (mL/g DM); $V_{1_{24}}$, total gas production for the fast pool after 24 h (mL/g DM); $V_{2_{24}}$, slow pool after 24 h (mL/g DM); $V_{1_{T_{0.5}}}$, fast-pool total-gas-production half-life (h); and $V_{2_{T_{0.5}}}$, slow pool half-life (h).

Species	Parameters	V_1	R_1	L	V_2	R_2	$\mathrm{V}_{\mathrm{Sch}}$	$V_{1_{24}}$	$V_{1_{T_{0.5}}}$	$V_{2_{24}}$	$V_{2_{T_{0.5}}}$	MAPE	RMSE	Adj R^2
Coprosma robusta	Value	71.9	0.017	1.71	50.8	0.095	122.8	27.7	28.9	50.8	7.7	−4.87	6.83	0.938
	SE	3.16	0.001	0.17	0.67	0.003								
	Lower 95% CI limit	65.8	0.016	1.38	49.5	0.089								
	Upper 95% CI limit	78.1	0.019	2.04	52.2	0.101								
Griselinia littoralis	Value	76.0	0.049	1.06	30.2	0.129	106.2	81.3	10.6	16.7	10.7	4.91	11.14	0.872
	SE	4.48	0.002	0.24	4.62	0.017								
	Lower 95% CI limit	67.2	0.045	0.59	21.1	0.095								
	Upper 95% CI limit	84.8	0.053	1.53	39.2	0.162								
Hoheria populnea	Value	33.9	0.021	1.03	78.1	0.073	112.0	16.5	23.0	77.4	8.4	−6.15	10.93	0.876
	SE	2.16	0.003	0.21	2.77	0.003								
	Lower 95% CI limit	29.7	0.016	0.62	72.7	0.066								
	Upper 95% CI limit	38.2	0.027	1.44	83.5	0.079								
Pittosporum crassifolium	Value	65.5	0.068	0.60	31.2	0.219	96.7	64.6	8.1	31.2	4.4	−2.11	6.70	0.922
	SE	2.06	0.002	0.13	2.11	0.019								
	Lower 95% CI limit	61.4	0.065	0.35	27.1	0.181								
	Upper 95% CI limit	69.5	0.071	0.84	35.3	0.257								
Salix schwerinii	Value	56.2	0.014	1.42	32.6	0.097	88.8	32.5	7.8	18.0	36.5	−4.09	3.71	0.950
	SE	4.10	0.001	0.22	0.44	0.003								
	Lower 95% CI limit	48.2	0.012	0.99	31.7	0.092								
	Upper 95% CI limit	64.2	0.015	1.86	33.4	0.103								

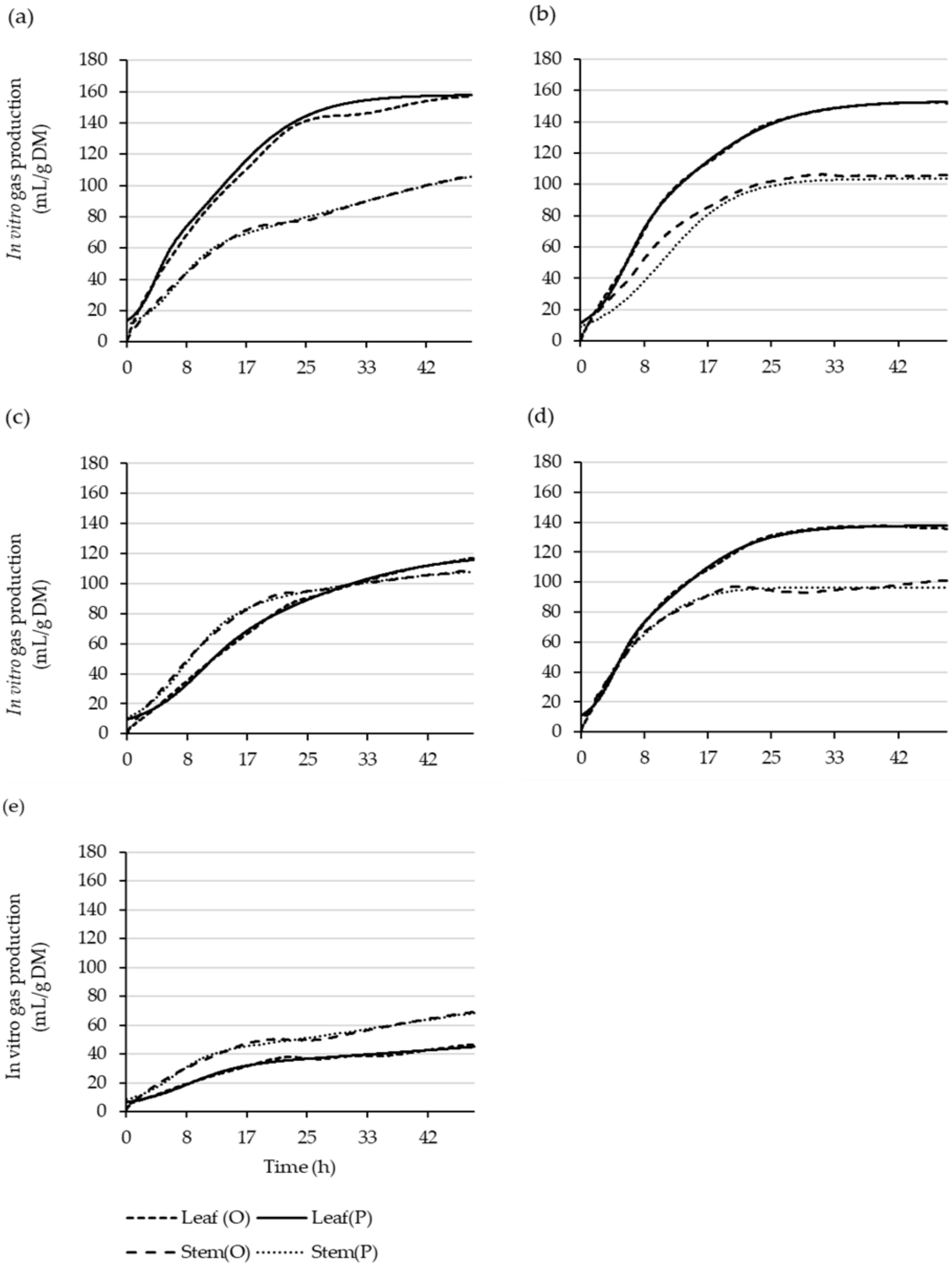

Figure 23. Observed (O) and the dual-pool-model-predicted (P) leaf and stem cumulative gas-production curves over 48 h for *Coprosma robusta* (**a**), *Griselinia littoralis* (**b**), *Hoheria populnea* (**c**), *Pittosporum crassifolium* (**d**), and *Salix schwerinii* (**e**).

5.3.4. In vitro fermentation end products

The *in vitro* fermentation end products expressed on a DDM basis were more elevated than those on a DM basis. However, the *in vitro* fermentation end products were found to have similar outcomes in the comparison of the native shrub species to the *S. schwerinii*, regardless of the analysis method. Therefore, the results are presented on a DM basis.

5.3.5. Volatile fatty acids and microbial biomass

The pH of the *in vitro* medium after fermentation ranged from 6.57 to 6.71 and differed ($p < 0.05$) among species for the leaves but not ($p > 0.05$) the stems (Table 21). The leaf pH was higher ($p < 0.05$) in the *S. schwerinii* than in native shrub species, except the *H. populnea*. For both the leaves and the stems, the *S. schwerinii* had nearly twice the ($p < 0.05$) MBM for the native shrub species, which did not differ ($p > 0.05$).

The VFA varied ($p < 0.05$) among the species for the leaves and stems, except for the valerate in the leaves and the propionate and isovalerate in the stems. The *Coprosma robusta* and *H. populnea* were similar ($p > 0.05$) and had higher ($p < 0.05$) *in vitro* medium acetate than the *P. crassifolium* and *S. schwerinii*, which did not differ ($p > 0.05$). The *Salix schwerinii* leaves produced higher ($p < 0.05$) propionate and lower ($p < 0.05$) butyrate than the native shrub species However, the *H. populnea* and *P. crassifolium* leaves were similar ($p > 0.05$) and had higher ($p < 0.05$) butyrate and valerate isomers than the other species. Consequently, the ratio of acetate to propionate was similar ($p > 0.05$) for the *S. schwerinii* and *P. crassifolium*, where it was lower ($p < 0.05$) than in the other species. The total VFA produced from the *in vitro* fermentation of the leaf material was similar ($p > 0.05$) in the native shrub species and approximately four times higher ($p < 0.05$) than in the *S. schwerinii*. The *S. schwerinii* stem *in vitro* medium had higher ($p < 0.05$) acetate and lower ($p < 0.05$) valerate than the other species, except the *C. robusta*, which was not different ($p > 0.05$) from any of the other species. The *S. schwerinii* had lower ($p < 0.05$) butyrate in the stem than the other species. However, the isobutyrate was higher in the *H. populnea* stem than in the other species, except for the *P. crassifolium*. The total VFA production from the *in vitro* fermentation of the stem material was higher in the native shrub species ($p < 0.05$) than in the *S. schwerinii*.

Table 21. The pH, total volatile fatty acids (VFA) in millimoles (tVFA, mM), percentage of respective VFA (acetate, propionate, isobutyrate, butyrate, isovalerate, valerate, %), ratio of acetate to propionate (A:P), and microbial biomass in milligrams per gram of dry matter (MBM, mg/g DM) for leaves and stems for native (*Coprosma robusta, Griselinia litoralis, Hoheria populnea,* and *Pittosporum crassifolium*) and an exotic (*Salix schwerinii*) shrub species with potential use as fodder sources in New Zealand.

Shrub Species	pH	Acetate	Propionate	Isobutyrate	Butyrate	Isovalerate	Valerate	Total VFA	A:P	MBM
					Leaves					
Coprosma robusta	6.57^{b}	63.1^{a}	22.2^{c}	0.15^{b}	13.8^{a}	0.11^{b}	0.69	27.5^{a}	2.9^{a}	101.3^{b}
Griselinia litoralis	6.57^{b}	61.2^{ab}	23.8^{c}	0.00^{c}	15.1^{a}	0.00^{b}	0.63	27.6^{a}	2.6^{a}	80.2^{b}
Hoheria populnea	6.62^{ab}	62.7^{a}	25.0^{bc}	0.38^{a}	10.4^{b}	0.58^{a}	0.89	24.5^{a}	2.5^{a}	106.4^{b}
Pittosporum crassifolium	6.57^{b}	57.6^{b}	27.6^{b}	0.33^{a}	13.1^{a}	0.52^{a}	0.92	28.8^{a}	2.1^{b}	112.5^{b}
Salix schwerinii	6.70^{a}	58.1^{b}	33.9^{a}	0.00^{c}	7.9^{c}	0.11^{b}	0.75	7.3^{b}	1.7^{b}	260.2^{a}
Pooled SE	0.027	0.98	0.73	0.033	0.57	0.062	0.070	0.99	0.09	9.88
					Stem					
Coprosma robusta	6.66	60.4^{ab}	25.0	0.00^{b}	14.2^{a}	0.00	0.74^{ab}	17.4^{a}	2.5	82.5^{b}
Griselinia litoralis	6.67	54.7^{b}	27.7	0.04^{b}	17.6^{a}	0.09	0.82^{a}	19.0^{a}	2.0	62.6^{b}
Hoheria populnea	6.66	55.8^{b}	27.9	0.29^{a}	15.1^{a}	0.38	1.03^{a}	19.9^{a}	2.0	70.1^{b}
Pittosporum crassifolium	6.67	53.3^{b}	31.9	0.09^{ab}	13.9^{a}	0.32	0.84^{a}	16.0^{a}	1.8	90.0^{b}
Salix schwerinii	6.71	68.6^{a}	25.9	0.00^{b}	7.7^{b}	0.00	0.29^{b}	9.6^{b}	2.7	144.4^{a}
Pooled SE	0.013	2.04	2.08	0.054	1.39	0.091	0.115	1.28	0.22	7.22

VFA, A:P and MBM with different superscripts in a column for the sample type are different at $p < 0.05$. Sample VFA value of 0.00 indicates the VFA was undetectable.

5.3.6. Fermentation Greenhouse Gases

The fermentative production of the greenhouse gases, carbon dioxide (CO_2) and methane (CH_4), and the carbon-dioxide equivalent (CO_2 Eq) differed among the shrub species for both the leaf and stem samples (Table 22). The production of greenhouse gases and CO_2 Eq was lower ($p < 0.05$) in the *S. schwerinii* than in the native shrub species for the leaf material. Similarly, the production of CO_2 from the fermentation of the stem material was also lower ($p < 0.05$) for the *S. schwerinii* compared to the native shrub species. The production of CH_4 from the fermentation of the stem material for the *S. schwerinii* was comparable ($p > 0.05$) to that of the *C. robusta* and *P. crassifolium,* and in relation to the production of CO_2 Eq, the *S. schwerinii* stems were similar to the *P. crassifolium*.

Table 22. Native shrubs (*Coprosma robusta, Griselinia litoralis, Hoheria populnea,* and *Pittosporum crassifolium*) and an exotic (*Salix schwerinii*) shrub species carbon dioxide (CO_2) and methane (CH_4) gas production (mL/g DM) and greenhouse carbon-dioxide equivalent (CO_2 Eq) (g/g DM) from the leaves and stems.

Shrub Species	CO_2	CH_4	CO_2 Eq
Leaves			
Coprosma robusta	76.5^{ab}	46.0^{a}	0.77^{a}
Griselin*ia litoralis*	76.3^{ab}	43.9^{a}	0.77^{a}
Hoheria populnea	64.2^{b}	37.8^{a}	0.66^{a}
Pittosp*orum crassifolium*	77.7^{a}	41.3^{a}	0.74^{a}
Salix schwerinii	17.2^{c}	8.6^{b}	0.15^{b}
Pooled SE	3.01	2.07	0.039
Edible stem			
Coprosma robusta	47.6^{a}	26.7^{ab}	0.45^{a}
Griselin*ia litoralis*	53.7^{a}	27.1^{a}	0.47^{a}
Hoheria populnea	54.7^{a}	28.0^{a}	0.49^{a}
Pittosp*orum crassifolium*	42.1^{a}	20.9^{ab}	0.36^{ab}
Salix schwerinii	23.5^{b}	14.9^{b}	0.25^{b}
Pooled SE	3.54	2.76	0.031

Fermentation gas (CO_2 and CH_4) and carbon-dioxide equivalent (CO_2 Eq) with different superscripts in a column for the sample type are different at $p< 0.05$.

5.4. Discussion

5.4.1. Shrubs Volatile Fatty Acid and Microbial Biomass Production

Approximately 70% of the caloric requirements of ruminants are met by the volatile fatty acids (VFA) produced by reticulorumen microbes (Burke et al., 2006). However, reticulorumen microbes' metabolism and, thus, the quantity and proportions of the VFA produced, are affected by nutrients and non-nutritive factors in the diet (Martel et al., 2011; Oba, 2011). The *in vitro* fermentation of the leaf and stem material from the native shrub species studied here resulted in more than three times the amount of total VFA (tVFA) compared to the *S. schwerinii*. The high tVFA yield in the native shrub species suggests that their nutrients were more digestible and could supply more ME to the animal than the *S. schwerinii*. The lower tVFA production during the *in vitro* fermentation of the *S. schwerinii* may have been due to the condensed tannins (CT), which are known to be present in *Salix spp* foliage (Oppong, 2001; McWilliam, 2005b; Mupeyo, 2011). However, the CT differences between the species in this study were not measured; therefore, this hypothesis cannot be tested and requires further attention.

Condensed tannins are complex polyphenolic compounds that bind to dietary proteins, polysaccharides, minerals, and microbial endogenous proteins and enzymes, thereby slowing microbial growth and proliferation and, hence, the production of VFA (Barry & McNabb, 1999; McSweeney et al., 2001). Although some pasture and fodder crops used in New Zealand contain small quantities of CT (Kemp, 2001; Waghorn et al., 2002), which reduce *in vitro* VFA production (Burke, 2006), *S. schwerinii* foliage has been reported to contain higher levels (<50 g CT/kg DM) (Douglas, 1996; Oppong, 2001). Further, the foliage CT concentration was found to be higher for *S. schwerinii* grown in hill country than on the fertile flat and rolling lands in New Zealand (Oppong, 2001), an environment where farmers are likely to plant native species. Comparatively, the tVFA produced by the native species (24.5 to 28.8 mM) was within the range reported for perennial ryegrass–white-clover pastures with up to 25% chicory (24.5 to 27.2 mM) (Al-Marashdeha et al., 2017), higher than for tropical shrubs (8.9 to 20.8 mM) (Jack, 2020), and lower than for leguminous shrubs (73.2 to 97.2 mM) (Meale et al., 2012), pasture grasses (perennial rye-grass, tall fescue, Yorkshire fog, phalaris and paspalum), leaves (112.1 mM) and stems (105.4 mM) (Chaves et al., 2006), and ryegrass–white-clover pastures with more than 25% chicory (29.8 to 33.4 mM) (Al-Marashdeha, 2017).

The *in vitro* fermentation of the native shrub species' leaves produced higher tVFA than that of the stems, which contrasted with that of the *S. schwerinii*. This was likely due to the native shrub species having more digestible dry matter in their leaves than their stems, and is to be expected, because stems contain higher levels of structural carbohydrates than leaves. This observation can be supported by the observation of higher VFA production levels from the *in vitro* digested dry matter for the native shrub species than the *S. schwerinii*. The higher tVFA production from *in vitro* fermentation of the *S.*

schwerinii stems compared to the leaves was likely due to the presence of CT in the leaves. The author (Oppong, 2001) observed higher CT levels in the leaves of *S. schwerinii* compared to their stems.

The primary VFAs produced in the rumen are acetate, propionate, and butyrate, with valerate and branched-chain VFAs only found in small quantities (Dijkstra, 1994). The proportion of non-glucogenic (combined acetate and butyrate) VFA produced from the *in vitro* fermentation of leaves and stems from the studied shrub species ranged from 66 to 76% of the tVFA. This was within the typical ranges reported for forages (64 to 80%) in New Zealand (Burke, 2006; Chaves, 2006; Sun et al., 2012b; Vibart et al., 2012), tropical shrubs (70.1 to 73.4%) (Jack, 2020), and leguminous (69.1 to 76.9%) and non-leguminous shrubs (73.4 to 79.6%) (Meale, 2012).

Proportionately, there was more acetate from the *in vitro* fermentation of the native species leaves than stems. By contrast, the *in vitro* fermentation of the *S. schwerinii* stems produced greater amounts of acetate compared to the leaves. Acetate is a lipogenic VFA that results from the fermentation of the structural carbohydrates (ADF and NDF) of forage and reduces with an increase in lignin content (Dijkstra, 1994; McSweeney, 2001). All the shrubs had more fiber (NDF and ADF) in their stems than in their leaves. Further, the lignin content was lower in the native shrub species stems than in their leaves, but the opposite for the *S. schwerinii*. Thus, typically, more acetate would be expected after the fermentation of the fibrous stems compared to the leaves. However, the proportion of acetate after the *in vitro* fermentation of the native species' stems was lower than from the leaves. In addition, more butyrate and propionate resulted from the *in vitro* fermentation of the native species' stems than from their leaves. This suggests that the native species' stems had more readily digestible carbohydrates than the leaves. This was likely because the shrubs were in a vegetative state and only new growth stems (i.e., less than 5 mm in diameter) were collected. Although they were not investigated, soluble and storage carbohydrates are typically high in new growth stems, and their fermentation results in elevated butyrate and propionate VFAs, respectively (Martel, 2011; Oba, 2011; Fleming et al., 2020; Dong et al., 2021).

The *in vitro* fermentation microbial biomass (MBM) yield was higher in the *S. schwerinii* than in the native species for both the leaf and the stem material and showed an inverse relationship to the tVFA production. The production of VFA *in vitro* corresponds to the growth and turnover of MBM and the subsequent degradation of feed substrates (Burke, 2006). However, the rate of growth and turnover of microbes depend on nutrient supply from the host diet and are affected by non-nutritive and inhibitory factors that hinder organic-matter digestibility (Martel, 2011; Oba, 2011). In contrast to the native species, the high *in vitro* MBM and low tVFA yield observed in the *S. schwerinii* suggests that there was low growth and turnover of microbes. This may have been due to the inhibitory effects of the CT (Oppong, 2001; Chaves, 2006; Haque, 2018; Albores-Moreno et al., 2019; Harun, 2019), which have been reported to be high in *S. schwerinii* (Douglas, 1996; Oppong, 2001). Nutritionally, feedstuffs with low digestibility have been shown to have low reticulorumen microbe turnover and, hence, reduced microbial protein supply to animals (Blümmel et al., 1997; Albores-Moreno, 2019; Harun, 2019).

5.4.2. In vitro Gas Production

The *in vitro* gas production was higher in the native species than in the *S. schwerinii*. The lower *in vitro* gas production in the *S. schwerinii* may be attributed to the presence of CT. On average, the *in vitro* gas production from the native shrubs (112.5 to 131.2 mL/g DM) was within the range previously reported for leguminous shrubs (113.7 to 148.5 mL/g DM), and higher than for the non-leguminous shrubs (28.1 to 101.4 mL/g DM), but lower than for the Moringa oleifera (187.0 mL/g DM) (Meale, 2012) and ryegrass (193.0 mL/g DM) (Fleming, 2020). The shrubs' *in vitro* gas production was consistent with the tVFA production and in inverse proportion to the MBM yield. This supports the results of previous studies, which showed a positive correlation between *in vitro* gas production and tVFA (Blümmel et al., 1999; Bhatt et al., 2019) and an inverse relationship with MBM yield (Blümmel, 1997).

The native species' *in vitro* fermentation gas production was higher in the leaves than in the stems, in contrast to the *S. schwerinii*. The high *in vitro* gas production in the native species leaves might have been associated with a higher production of acetate relative to butyrate and propionate VFAs (Haque, 2018), contrary to the stems. The stoichiometry of VFA proportions can be used to estimate the amount of gas production when feed substrates are fermented *in vitro* (Blümmel, 1997). The fermentative formation of acetate has been reported to result in higher *in vitro* gas production (Haque, 2018; Harun, 2019), explaining the high *in vitro* gas produced by the native species' leaves compared to their stems. Another factor that may have contributed to the higher *in vitro* gas production in the native species leaves is the higher CP content of the leaves compared to the stems. Dietary CP provides reticulorumen microbes with nitrogen, which is essential for growth and proliferation, enhancing carbohydrate degradation, resulting in increased gas production (Haque, 2018).

Among the native species, the *H. populnea* leaves had lower *in vitro* gas production despite having a higher CP. The lower *in vitro* gas production by the *H. populnea* leaves can likely be explained by the presence of higher ash content (11.6% DM) than in all the other shrubs. Ash content suggests the presence of minerals that are inorganic and unfermentable (Harun, 2019). Similar ash content in *H. populnea* leaves has also been reported previously (Sims et al., 2018; Simmonds, 2020) and was within the range of that of forages (Burke, 2006), pasture grass (perennial rye-grass, tall fescue, Yorkshire fog, phalaris, and paspalum), and leaves (8.9 to 12.1% DM), but higher than for stems (5.5 to 8.9% DM) (Chaves, 2006).

5.4.3. *In vitro* Fermentation Kinetics

Mathematical non-linear models are essential tools that can be used to describe *in vitro* fermentation gas production using parameters that have biological interpretations (Assis, 2021). The models vary in their complexity and differ in the Equation structures and parameters (pools or compartments) that are applied in their predictions of *in vitro* fermentation gas production (Wang, 2011). In this study, the single-pool exponential model of (Orskov, 1979) and the dual-pool logistic model developed by (Schofield, 1994) were applied to fit the *in vitro* fermentation gas production. Both the models ranked the predicted *in vitro* fermentation gas production for the shrubs' leaves similarly to the measured *in vitro* fermentation total gas production. However, the models showed discrepancies in their ranking of the predicted *in vitro* fermentation gas production for *C. robusta*, *G. littoralis* and *H. populnea* stems. The stems of these three species had similar *in vitro* fermentation total gas production measurement and therefore the discrepancies between the models are likely due to their fixed inflection points, which affected the predicted rate and asymptotic gas production (Wang, 2011). However, both the single- and dual-pool models had good predictive accuracy (MAPE) and explained a greater proportion of the variability (Adjusted R squared) between the measured and predicted *in vitro* fermentation gas production of the shrubs, except the *S. schwerinii* leaves. The lower accuracy and higher variability of the *S. schwerinii* leaves is likely to have been due to the inconsistently low gas production observed in the measured *in vitro* fermentation gas production.

The single-pool model produced negative prediction for the *in vitro* fermentation gas production from the immediately soluble fraction (a, mL/g DM) for the native species' leaves. Similarly, negative value of "a" in the single pool model was predicted for the native species' stems, except for the *C. robusta*. A negative "a" value was a mathematical anomaly for the model, indicating negative gas production, which is biologically incorrect. This showed the mathematical limitations of the single-pool model in predicting the *in vitro* fermentation gas production for the native shrubs. Moreover, the single-pool model numerically overestimated the *in vitro* fermentation gas production of the native species, except the *H. populnea* stems. This can likely be attributed to the model assumption of a constant rate of fermentation (Groot et al., 1996; Wang et al., 2013; Dos Santos Cabral et al., 2019; da Silva Zornitta et al., 2021), despite the fact that the native shrubs' leaves had varying fermentable nutrients. Results from previous studies also demonstrated these limitations of using the single-pool model in predicting the *in vitro* fermentation gas production on feeds with mixed fermentable substrates (Wang, 2011; Assis, 2021; da Silva Zornitta, 2021).

The dual-pool model predicted higher *in vitro* fermentation gas production and longer gas-production half-life for the fast pool for the native species' leaves, in contrast to the *S. schwerinii*. This observation suggests that the nutrients in the leaves of the native shrub species were readily fermentable, which is supported by the shrubs' observed nutrient composition, tVFA, and total gas production in this study. However, the model predicted higher *in vitro* fermentation gas production from the slow pool for the *H. populnea* stems. This was expected, because the *H. populnea* stems contained higher structural carbohydrates (NDF and ADF) compared to the other shrubs. The higher *in vitro* fermentation gas production for fast pool and longer gas-production half-life for the slow pool for the *S. schwerinii* stems support the observed *in vitro* fermentation tVFA proportions and the measured total gas production in this study. The coherence of the dual-pool model in predicting the *in vitro* fermentation gas production for the studied shrubs supported earlier studies using different forages (Pitt, 1999; Tedeschi, 2008; Wang, 2011; Assis, 2021). However, the model numerically underestimated the *in vitro* gas production for all the shrubs, except the *C. robusta* leaves and *H. populnea* stems, which it overestimated. Therefore, there is a need for a comparison of the dual-pool model with other multicompartment models to determine the model that can best describe the *in vitro* fermentation gas production for the studied shrubs.

5.4.4. Greenhouse-gas emission from the shrubs

The greenhouse-gas production was higher for the native shrub species than for the *S. schwerinii*. In addition, the native species' leaves produced more greenhouse gases than the stems, while the opposite tendency was observed for the *S. schwerinii*. Proportionately, the *in vitro* production of CH_4 gas was greater in the native species' leaves than in their stems, while the opposite was true for the *S. schwerinii*. The CH_4 production by the *S. schwerinii* leaves (8.6 mL/g DM) and stems (14.9 mL/g DM) were lower, while those of the native species' leaves (37.8 to 46.0 mL/g DM) and stems (20.9 to 29 mL/g DM) were within the ranges reported for New Zealand pastures (17.6 to 58.5 mL/g DM) (Meads et al., 2020). Averaging the leaves and stems, the native shrubs had more CH_4 gas than the high-CT browse (18.3 to 29.2 mL/g DM), less than the *Moringa stenopetala*, and amounts within the range reported for low-CT shrubs (34.2 to 40.8 mL/g DM) (Tirfessa & Tolera, 2020). On the other hand, the *S. schwerinii* had lower average leaf and stem CH_4 gas than the low- and no-CT browse species and values within the range of high-CT browse species (Tirfessa, 2020). The low-enteric-fermentation greenhouse-gas production by the *S. schwerinii* may be attributed to the presence of CT. Results from studies using leguminous and non-leguminous shrubs (Ramírez-Restrepo et al., 2010; Meale, 2012; Mueller-Harvey et al., 2019) have shown that CT in forages causes a reduction in enteric-fermentation greenhouse-gas (Waghorn, 2002; Min et al., 2020) as was observed with *S. schwerinii* in the current study.

Carbon dioxide (CO_2) and methane (CH_4) are the major enteric-fermentation greenhouse gases (GHGs) produced by ruminants (Haque, 2018). Compared to CO_2 gas, CH_4 gas is more important because it is more potent, equating to 25 carbon-dioxide equivalents (CO_2 Eq) in global-warming potential (Haque, 2018; Bhatt, 2019). Further, enteric-fermentation CH_4 gas accounts for approximately 84% of the gross CH_4 emissions in New Zealand (Sun et al., 2015; Ministry for the Environment, 2021). However, the amount and proportions of the enteric-fermentation gases produced are dependent on the nutritional composition of ruminant feeds, as this influences reticulorumen microbial populations and fermentation pathways (Clark et al., 2011; Haque, 2018). A higher acetate proportion results in higher CH_4 emissions (Johnson & Johnson, 1995; Van Nevel, 1996; Haque, 2018), as was observed in the native species leaves. Acetogenesis causes the release of hydrogen ions, which are utilized by methanogenic reticulorumen microbes to reduce CO_2, thereby releasing CH_4 as metabolites (Johnson, 1995; Sun et al., 2012a).

The production of CH_4 gas by methanogenic microbes results in a 2 to 12% loss of energy from ingested feeds (Johnson, 1995; Van Nevel, 1996; Pinares-Patiño et al., 2013; New Zealand Agricultural Greenhouse Gas Research Centre & Pastoral Greenhouse Gas Research Consortium, 2016). On the other hand, butyrate and propionate formation were elevated from the *in vitro* fermentation of native species stems. Butyrate and propionate syntheses act as hydrogen sinks and compete for hydrogen ions with methanogenic rumen microbes, thereby reducing CH_4 and promoting CO_2-production metabolic pathways (Van Nevel, 1996; Clark, 2011) explaining the depressed CH_4 production in the *in vitro* fermentation of the native species' stems.

5.5. Conclusion

The results in the current study show that the fermentation of the leaf and stem material from the native shrub species resulted in higher *in vitro* total gas production than in the *S. schwerinii*. The single- and dual-pool models used to predict the *in vitro* fermentation total gas production for the shrubs had a satisfactory fit. However, the single-pool model was biologically incorrect in predicting negative *in vitro* total gas production from the immediately soluble fraction of the native shrubs. On the other hand, the dual-pool model predicted the *in vitro* fermentation total gas production better and was coherent with the measured *in vitro* fermentation end products. The native shrubs produced greater amounts of volatile fatty acids in the *in vitro* fermentation of the leaves and stems than the *S. schwerinii*. Conversely, the *S. schwerinii* yielded more microbial biomass from the *in vitro* fermentation of the leaves and stems than the native species. The *in vitro* fermentation characteristics of the native species' leaves and stems suggest that they were more digestible and could provide more energy and microbial proteins to animals compared to the *S. schwerinii* if consumed. Comparing among the native shrubs, *H. populnea* leaves would be superior when consumed by providing higher levels of CP and yielding lower *in vitro* fermentation total gas production and emitting lower volumes of greenhouse gases. This study suggests that when consumed by ruminant livestock, native shrubs can provide adequate energy and microbial protein, and that the greenhouse-gas production from these species is generally within the ranges reported for typical New Zealand pastures. Further studies are required to determine animal preference and intake and to quantify GHG production in vivo.

Forward to Chapter 6

Chapters 4 and 5 evaluated the nutritional value of native shrubs and compared them to osier willow in terms of their nutritional composition and *in vitro* fermentation characteristics, respectively. However, the foliage biomass of the native shrubs remains unknown. To address this, Chapter 6 estimated the aboveground biomass accumulation and partitioning into various components (foliage, branch, and stem). Chapter 6 also developed allometric functions to estimate biomass variables and carbon stock.

Chapter 6: Allometric Functions for Estimating Biomass and Carbon Stock of Three New Zealand Native Shrub Species

Abstract

The clearing of native vegetation and sowing of exotic pastures on hill country sheep and beef farms over the last 180 years has caused remarkable negative ecosystem impacts. Exotic trees and shrubs have been extensively studied and used to alleviate the negative impacts. However, there are few studies on native shrubs despite their numerous benefits and potential as an alternative to the exotic species. This study aimed to estimate biomass variables, develop, and compare predictive allometric functions for the biomass variables and estimate carbon stock based on three browsable native shrubs (*Coprosma robusta* (Karamū), *Pittosporum crassifolium* (Karo) and *Melicytus ramiflorus* (Māhoe) common in New Zealand. Results showed the native shrubs differed in foliage and branch biomass ($p<0.05$) but not stem and above ground biomass ($p>0.05$). The generalized allometric function for foliage and aboveground biomass was comparable ($p>0.05$) to the species-specific allometric functions. Estimated carbon stock accumulation over 50 years was highest for *P. crassifolium* (532.1 t CO_2/ha) and this was 62.8% and 60.0% higher than for *C. robusta* and *M. ramiflorus*, respectively. In conclusion, the generalized allometric functions in this study can be used to estimate foliage and aboveground biomass for New Zealand native shrubs growing under similar conditions to the study sites. Additionally, mixed native shrub species planted on farm can have greater benefits as the different species would complement each other for foliage production and carbon sequestration.

Key words: Native shrubs, biomass, allometric functions, carbon stock,

6.1. Introduction

The New Zealand ecosystem has undergone remarkable transformation from native forest and shrub land to pasturelands over the last 180 years, resulting in a decline of approximately 70% of the native vegetation cover (Marden, 2005b; Allen, 2013; Kerr, 2014). Currently, native woody vegetation only covers approximately 30% of New Zealand's land mass, of which 17% are found on sheep and beef cattle farms (Norton, 2018; Kimberley et al., 2021; Pannell, 2021). Approximately 16% of the native woody vegetation is shrubs comprising nearly 400 species (Merrett, 2006) with approximately 80% endemic to New Zealand (Brooker, 1989). On these sheep and beef cattle farms, native woody vegetation is mainly found on the inutilizable steep slopes and along riparian areas (Marden, 2005b; Dodd, 2007; Norton, 2018). New Zealand's native vegetation has ecological, social, and cultural importance (Allen, 2013; Bergin, 2014b; Pannell, 2021) but its role in the farmed landscapes has only recently received attention. When planted on farm, native vegetation can stabilize steep slopes for erosion control (Marden, 2005b), sequester carbon dioxide (Carver, 2017; Kimberley, 2021) and the palatable species can provide some forage to farmed ruminants (Chapter 3). However, studies on the biomass yield and carbon sequestration potential of most New Zealand native vegetation are scant because of their numerous species range and the preference for exotic species for wood production (Marden, 2005b, 2018b; Kimberley, 2014; Case & Ryan, 2020).

Biomass can vary among plant species, plant parts, and for a particular species across geographical locations (Kimberley, 2014; Marden, 2018b). Variations in biomass for plant species can be attributed to differences in phylogeny, phenology, structural composition, and physiognomy (Poorter, 2012a; Poorter et al., 2015). Variation in plant part biomass can be due to differences in physiological, biochemical, and structural functions (Poorter, 2012a). Geographical location influences accumulation of plant's biomass and partitioning to the various parts of the plant through the effects of ambient environment and soil resources (Marden, 2005b; McAlpine & Jesson, 2007; Poorter, 2012a). However, biomass partitioning to various parts of the plant follows a species-specific relationship that can be empirically quantified and related to measurable morphometric parameters using allometric functions (Poorter, 2012a; Mason, 2014; Sileshi, 2014). Although the most accurate method for biomass estimation is directly harvesting and weighing of individual plants, it's costly, tedious, and destructive

(Roxburgh et al., 2015). Conversely, developing biomass allometric functions requires fewer samples that represents the full range of the plant growth (Sileshi, 2014). Once developed, the allometric functions can be a cost effective and efficient method of species-specific biomass estimation for plants in similar conditions (Roxburgh, 2015). Moreover, sampling can be expanded to include mixed species and multiple locations to develop location specific and generalized biomass allometric functions (Sileshi, 2014). The developed biomass allometric functions can further be used as the basis to estimate carbon content and carbon stock sequestered (Beets et al., 2012). In New Zealand, allometric functions for biomass and carbon stock for wood production species have been extensively developed (Moore, 2010; Beets, 2012; Kimberley, 2014; Steward et al., 2014), but very few exist for native species particularly for those with forage potential (Beets, 2014b; Kimberley, 2014, 2021).

Among the current environmental concerns in New Zealand are erosion control, biodiversity conservation, reduction of waterway pollution and greenhouse gas mitigation (Ministry for the Environment & Stats NZ, 2019). Planting native vegetation on the steep slopes of hill country sheep and beef farms can provide multiple benefits that contribute to the alleviation of these environmental concerns (Marden, 2005b; Bergin, 2014b; MacGibbon, 2014; Kimberley, 2021). Moreover, use of browsable native shrubs can be of further benefit to farmers by providing a supplementary fodder source during seasons when pastures are low in quality and or quantity. However, studies estimating total aboveground biomass, forage biomass yield, and carbon stock for New Zealand native shrubs with forage potential are lacking. Estimation of these parameters for native shrubs would enhance comparison with other species and improve predictions for biomass and carbon stock. Therefore, the objectives of this study were to: (1) estimate foliage, branch, stem, and the total above ground biomass for three common New Zealand native shrub species (*Coprosma robusta*, *Pittosporum crassifolium* and *Melicytus ramiflorus*), (2) develop and compare species, location, and generalized New Zealand native shrub biomass allometric models, and (3) estimate their carbon stock.

6.2. Materials and Methods

6.2.1. Shrub description

The native shrub species used in this study were chosen because they are endemic and widely distributed in New Zealand (de Lange, 2022a, 2022d, 2022c). *Coprosma* *robusta* (Karamū) is a vigorous shrub that grows up to 6 m in an erect or somewhat spreading habit and characterized with numerous foliated branches (Salmon, 1996; de Lange, 2022a). It is commonly found throughout coastal, lowland, montane and within shrublands and open areas in forests (Metcalf, 2011; de Lange, 2022a). *Pittosporum crassifolium* (Karo) is a hardy shrub with an erect growth of up to 9 m and fastigiate branches (Metcalf, 2011). It commonly occurs around forest margins and streamside locations mainly near coastal areas (Salmon, 1996; Metcalf, 2011). It favors steep slopes, cliff faces, and dune forests (de Lange, 2022d). *Melicytus ramiflorus* (Māhoe) grows as a spreading shrub or small tree up to 15 m, with heavy branching near the ground and with a trunk diameter of up to 60 cm (Salmon, 1996; Metcalf, 2011; de Lange, 2022c). Māhoe is common on coastal, lowland, lower montane forests, and scrublands in mainly partially cleared areas (Salmon, 1996; de Lange, 2022c).

6.2.2. Study sites description

The three shrub species were sourced from: (a) a shrub trial site at Massey University Dairy4 farm, (b) natural vegetation at Massey University and (c) natural vegetation reserves on Limestone Downs farm. Massey University Dairy4 trial site (Lat -40.401447, Long 175.617912) and Massey University Campus are located approximately five kilometers south of Palmerston North city in Manawatu district, New Zealand. The Limestone Downs farm is located (Lat -37.47775, Long 174.759) approximately 15 kilometers south of Port Waikato in Waikato district (Zanders et al., 1999; Mcgill et al., 2010; Pullanagari et al., 2018). Geographically, Massey University is inland in contrast to Limestone Downs farm that is coastal. The climatic conditions experienced in the two areas are shown in Table 23. Massey University Dairy4 farm trial site is on a steep slope (>25°) with a southerly aspect dominated by Tokomaru silt loam soil at the top and Ohakea silt at the bottom of the slope (Cowie, 1977). Areas of natural native vegetation near the Massey University campus are found on a variety of soil types, slopes, and aspects but Tokomaru silt loam is dominant. The relief on Limestone Downs farm consists of flat (46%), easy (42%) and steep (12%) slopes with a predominant southwest aspect (Murray & Yule, 2007). Soils vary across Limestone Downs farm ranging from peat on the low marshy areas to volcanic soils on the higher grounds (Murray, 2007). However, Dunmore silt loam and Kohemarere hill soils are the dominant soil types (Zanders, 1999). Approximately 13% of vegetation on the farm is comprised of mixed native species in natural stands mainly on the steeper slopes (Zanders, 1999).

Table 23. Summarized long-term seasonal climatic conditions for Palmerston north district (Chappell, 2015) and West coast of Waikato (Chappell, 2013)

Climate parameters		Site	Season			
			Summer	Autumn	Winter	Spring
Temperature	Mean (°C)	Palmerston North	17.4	13.8	9.0	12.4
		Waikato	18.7	16.9	12.5	14.0
Rainfall	Total (mm)	Palmerston North	222.0	189.0	246.0	43.7
		Waikato	249.0	255.0	291.0	277.0
	Percent of total rainfall (%)	Palmerston North	25.0	21.0	27.0	26.0
		Waikato	23.0	24.0	27.0	25.0
	Average monthly rain days (d)	Palmerston North	11.7	12.7	17.7	15.3
		Waikato	10.3	12.0	18.0	13.7

6.2.3. *Shrub measurements, destructive sampling, and sample processing*

A total of 54 shrubs were randomly sampled (Table 24) between July 2021 and May 2022 from the study sites. The sample size was limited due to restrictions of cutting native shrubs in conservation areas in New Zealand (Beets, 2012). However, a sample size of more than 50 shrubs representing the full range of the measured parameters can be used to develop allometric models (Sileshi, 2014; Huynh et al., 2021). Sampled shrub numbers varied among the species and location due to species dominance within each location. Shrubs were considered for sampling if they had intact morphology and their basal stem diameter did not exceed 10 cm. Shrubs with <10 cm diameter are the most prevalent in the natural reserves and has foliage that can be easily accessed and browsed by farmed ruminants if planted on the farm. Damaged shrubs due to wind or browsing e.g., those along the fence periphery were avoided.

Table 24. Number of shrubs per species destructively sampled from Limestone Down farm and Massey University natural reserves and Massey University Dairy4 farm trial site.

Site	Shrub species (numbers)		
	C. robusta	*P. crassifolium*	*M. ramiflorus*
Limestone Down farm natural reserves	12	14	9
Massey University natural reserves	3	3	5
Massey University Dairy4 farm trial site	3	2	3
Total	18	19	17

Prior to destructive sampling, individual shrub morphometric parameters including stem basal diameter (D, cm) and height (H, m) were measured. Vernier calipers was used to measure stem diameters (d_i, cm) less than 2 cm and a diameter tape was used for d_i greater than 2cm (Philip, 1994; Conti, 2013; Beets et al., 2014a; Mason, 2014). The diameters were measured over the bark (Marden, 2018b) above the root collar and approximately 10 cm above the ground (Huff et al., 2017). Two orthogonal diameters per stem (d_1 and d_2) were measured when using the Vernier calipers and the square root of their product taken as the value of d_i (Beets, 2014a; Mason, 2014). Orthogonal diameter were used to ensure that Vernier caliper measurements compared to those of diameter tape (Mason, 2014). In multi-stemmed shrubs, stems d_i per shrub were summed and the square root used as the value of *D*. Shrubs were considered to be multi-stemmed if their stem forked below approximately 10 cm (Beets, 2014a; Mason, 2014).

Shrub H was measured using a telescopic levelling staff from the highest ground level adjacent to the shrub base to the peak growing point of the longest stem. Positioning the telescopic levelling staff on the highest ground level of the shrub ensured measurements were consistent and unbiased to the slope in the sampling areas (Philip, 1994; Conti, 2013).

After measuring the morphometric parameters, the shrubs were cut at ground level and their age estimated by counting the annual basal stem rings. The shrub was then separated into three components: the stem (*S*), branches (*B*), and foliage (*F*), because each differs in moisture content and density, and therefore biomass (Ketterings et al., 2001; Picard, 2012). In this study, the stem component was the woody growth that linked the branches to the roots. Branches were the woody parts that supported branchlets and connected them to the stem. Foliage component consisted of the edible branchlets less than 5 mm in diameter, buds, leaves, flowers, and fruits. Branchlets with diameter less than 5 mm contain mostly soft new growth, which can be consumed by livestock (Kemp, 2001; New Zealand Poplar and Willow Research Trust, 2013). Each component for an individual shrub was weighed separately using a hanging digital scale (Wedderburn WS60330K, accuracy=0.01 kg). A representative fresh sample of each component was collected, weighed, labeled and stored in sealed plastic bags and transported to the laboratory for estimation of the biomass. All fresh samples were oven dried at 80°C until there was no notable change in weight after three consecutive weighings (Picard, 2012). Because the stem samples were less than 20 cm , they were not debarked prior to oven drying (Picard, 2012).

6.2.4. Estimation of shrub aboveground and total biomass

Organic matter in rooted plants can be partitioned into aboveground biomass (*ABM,* kg) and belowground biomass (*BBM*, kg) (Picard, 2012). The *ABM* includes the stem, branches, leaves, and reproductive parts while the *BBM* comprises the root system (Beets, 2012). Shrub *ABM* was estimated as the sum of each component's biomass (*cBM*, kg) (*S*, *B* and *F*). Each *cBM* was estimated as the proportion of sample oven dried weight (*N*) to sample fresh weight (*W*) factored to the component fresh weight (*C)* (Mohan et al., 2020) (Equation 15). Earlier studies have estimated that *ABM* and *BBM* account for approximately 75% and 25%, respectively, of total biomass (*TBM*) (Marden, 2005b, 2018b; Beets, 2012). Since *BBM* was not measured in this study, it was assumed to be approximately 33% of *ABM* and *TBM* as 1.33 of *ABM*.

Equation 15 $$cBM_i = \left({N_i}/{W_i}\right) \times C_i$$

Where cBM_i was component (S, B or F) biomass, W_i sample fresh weight, N_i sample oven dried weight and C_i component fresh weight of the i^{th} component.

6.3. Statistical analysis and allometric models' parameters estimation

Statistical analysis and estimation of allometric model parameters was carried out using SAS software version 9.4 (SAS Institute, Cary, NC, USA). The data was tested for normality using the Shapiro-Wilk Test (Yap & Sim, 2011; Wijekularathna et al., 2020) and for homogeneity of variances using Levene's test (Parra-Frutos, 2013; Paul et al., 2013). The tests showed *cBM* and *ABM* data were non-normal ($p<0.001$) but had homogenous variances ($p>0.05$). As a result, the data was transformed using a natural logarithm to conform to the normal distribution assumption before statistical analysis. However, back transforming logarithmic data has been shown to introduce a downward bias on the response variable (Paul, 2013; Bulmer et al., 2016; Flade et al., 2020). Therefore, a correction factor (*cf*) (equation 16) was calculated for back-transformed response variables (Paul, 2013) and the delta method was used to correct the standard errors to the original scale (equation 17) (Onofri et al., 2010).

Equation 16 $$cf = e^{(MSE^2/2)}$$

Equation 17 $$SE_b = e^{(y)_i} \times SE_i$$

Where MSE is mean square errors, SE_b back transformed standard errors, y_i transformed response variable and SE_i transformed standard errors.

6.3.1. Comparison of shrub biomass among species and between locations

The analysis of covariance (ANCOVA) in the mixed linear model procedure (Proc MIXED) was used to compare *cBM* and *ABM* for the fixed effects (locations and shrub species) using *D* and *H* as covariates. The covariates were used to reduce variability (Mahmood et al., 2007; Yang & Juskiw, 2011) in *cBM* and *ABM* due to heterogeneity of the shrubs sampling environments. In addition, interactions of the fixed effects, comparison between the fixed effects and covariates were added to the model. The fixed effects interaction was utilized to allow for assessment of their joint influence on *cBM* and *ABM,* while the interaction between the fixed effects and covariates tested for differences in the slopes of *cBM* and *ABM* for the fixed effects (Yang, 2011).

6.3.2. Developing shrub biomass allometric models

It is known that biomass in plants can vary among species and across locations, which can affect the predictive accuracy of allometric models (Ketterings, 2001; Nyamjav et al., 2020). Native shrubs used in this study were of three genera and from two locations (Manawatu and Waikato districts). Therefore, three groups: (a) species-specific, (b) location specific, and (c) generalized allometric models were developed and compared. Species-specific models considered the shrub genus separately regardless of the source. Location specific models were indiscriminate of shrub genera while the generalized models utilized all data regardless of shrub genera or location.

The allometry relating biomass and morphometric parameters are often non-linear and based on polynomial and power functions (Ketterings, 2001; Mascaro et al., 2011; He et al., 2018). Morphometric parameters widely used in biomass allometry are *D* and *H* because they are easily measurable and are corelated to other measured and derived parameters. However, *D* is a better predictor of site-specific biomass estimation (Mascaro, 2011; Ma, 2018) and inclusion of *H* can improve prediction accuracy for generalized biomass models (Ketterings, 2001; Ali et al., 2015). In this study, a univariate and two bivariate power functions were chosen to derive parameter estimates predicting *ABM* and *cBM* for the three groups of allometric models. The univariate function used *D* (Equation 18) while *H* was included in the two bivariate functions (Equation 19 and 20). Equations 18 and 19 were chosen because they are extensively used in shrub and tree biomass predictions (Beets, 2012; Roxburgh, 2015; Huynh et al., 2022) while equation 20 has been used for New Zealand native shrubs (Beets, 2014a). Unlike Equations 18 and 19 that used measured parameters, equation 20 used stem volume ($BA \times H$), where BA is basal area derived from parameter from D (equation 21).

Equation 18 $$ABM\ or\ cBM = a \times D^{b}$$

Equation 19 $$ABMor\ cBM = a \times D^{b} \times H^{f}$$

Equation 20 $$ABMor\ cBM = a \times (BA \times H)^{b}$$

Equation 21 $$BA = \pi \times \left({D^{2}}/{4}\right)$$

Where *f*, *a* and *b* are model parameters.

Use of power function equations assumes homogeneity of errors (Baskerville, 1972; Mascaro, 2011). However, this assumption was not applicable in this study because of the asymmetric distribution of *cBM* and *ABM* data. In addition, young trees and shrubs (trunk diameter <10 cm) in natural habitats, like used in this study can exhibit heterogenous physiognomy that can result in systemic bias in parameters estimates when using power functions (Mascaro, 2011; Sileshi, 2014). Therefore, natural logarithm forms of the power functions (equation 22, 23 and 24) were used to linearise the allometry and reduce heteroscedasticity (Beets, 2012; Poorter, 2012a; Paul, 2013; Mason, 2014).

Equation 22 $$ln(ABM)\ or\ ln\ (cBM) = ln\ (a) + b \times ln\ (D)$$

Equation 23 $$ln(ABM)\ or\ ln\ (cBM) = ln\ (a) + b \times ln(D) + f \times ln\ (H)$$

Equation 24 $$ln(ABM)\ or\ ln\ (cBM) = ln(a) + b \times ln(BA \times H)$$

Parameter estimates and accuracy of allometric models can differ depending on the method and sample size used (Sileshi, 2014). Three methods (ordinary least square (OLS), maximum likelihood (ML) and Bayesian analysis) that are commonly used in biomass allometric models (Beets, 2012; Sileshi, 2014) were considered. The methods were tested and compared using the model fit diagnostic statistics (Akaike information criterion (AIC), root mean square error (RMSE) and adjusted coefficient of determination (Adjusted R^2)) for suitability in fitting the study data. The most accurate model should have both low AIC and RMSE and a high Adjusted R^2d (Sileshi, 2014; Cavanaugh & Neath, 2019).

The linear regression OLS produced unrealistic fit diagnostic statistics and was avoided. In addition, OLS method requires a large sample size (>50) for accurate and appropriate parameter estimation (Sileshi, 2014) and this threshold was not met for the species and locations specific models. Although Bayesian analysis is more robust and requires a much smaller sample size (Sileshi, 2014), it produced similar parameter estimates to the ML method. Therefore, the ML method was used to fit *cBM* and *ABM* data using both univariate and bivariate functions to estimate parameters for the three model groups (generalized, species-specific, and site-specific). The best model for *cBM* and *ABM* across the three groups was chosen based on their fit diagnostic statistics (AIC, RMSE, Adjusted R^2). However, only one functional form that was superior across the three groups was selected for *ABM* and each *cBM*. A *t*-test (equation 25) was used to test for differences in estimated parameters between the best generalized model and species and location specific models. Similarity of the estimated parameters for the three groups can support the use of the generalized model in predicting biomass for the New Zealand native shrubs.

Equation 25 $$t = (p_1 - p_2)/\sqrt{(SE^2{}_1 + SE^2{}_2)}$$

Where p_1 and $SE^2{}_1$ are parameters and standard errors for the generalized model and p_2 and $SE^2{}_2$ are parameters and standard errors for species and location specific models.

6.3.3. Estimating shrub carbon content and sequestered carbon stock

The relationship between age and carbon accumulation in plants is well described by the Gompertz model because it assumes asymptotic growth as observed in woody plants (Easdale, 2018). Therefore, a Gompertz model (equation 12) was fitted to relate shrub age to the estimated *TBM* (section 6.2.4) for the selected best models (generalized, species-specific and location specific) (section 6.3.2). Since carbon content was not measured, it was estimated to be approximately 50% of *TBM* as this value is widely utilized in New Zealand (Scott et al., 2000; Beets, 2012, 2014a; Schwendenmann & Mitchell, 2014). The derived carbon content was multiplied with carbon dioxide (CO_2) molecular weight ratio of 3.67 to estimate sequestered CO_2 stock (Kimberley, 2014; Easdale, 2018). However, biomass accumulation and therefore sequestered CO_2 stock is affected by plant density (Bergin, 2014b; Easdale, 2018). The typical density for mixed young shrubs and small trees in restoration natural reserves in New Zealand can range between 5,000 to more than 10,000 stems per hectare (sph) (Bergin, 2014b; Te Uru Rākau, 2020). Therefore, an average initial shrub density of 8,000 sph was assumed in estimation of the sequestered CO_2 stock over 50 years. The model groups were compared on their total cumulative CO_2 stock over 50 years, their mean annual CO_2 stock increment (MAI) and current annual CO_2 stock increment (CAI) (Kimberley, 2021).

6.4. Results

6.4.1. Characteristics of the sampled shrub

Descriptive statistics for the sampled shrubs measurements in Limestone Downs and Massey University and the two sites combined are shown in Table 25. Sampled shrubs age ranged from 3 to 7 years with *M. ramiflorus* having the oldest and *C. robusta* the youngest mean age. Mean stem diameter was greatest for *M. ramiflorus* in Limestone Downs and lowest for the same species at Massey University. Overall, *P. crassifolium* was the tallest and *C. robusta* the shortest.

6.4.2. Effects of variables on biomass estimation

Both D (ln D) and H (ln H) significantly ($p<0.001$) determined shrub biomass variables except for foliage biomass, which was not affected by H ($p>0.05$) (Table 26). Shrub species had a significant ($p<0.05$) effect, but site had no effect ($p>0.05$) on biomass variables except for branch biomass ($p<0.05$). There was no interaction ($p>0.05$) between species and site for any biomass variable. The slope coefficients for all shrub biomass variables did not differ ($p>0.05$) between the sites and among shrub species with changes in H. However, the slope coefficients for branch biomass differed between sites ($p>0.05$) and slope coefficients for stem biomass differed among species ($p>0.01$) with changes in D.

Table 25. Descriptive statistics (mean ± standard deviations) for age (years), basal diameter (D, cm) and height (H, m) of the sampled shrubs in Limestone Downs and Massey University and the two sites combined (All)

Site	n	Age	*D*	*H*
		Limestone Downs		
Coprosma robusta	12	3.8±1.19	3.7±1.54	1.8±0.80
Melicytus ramiflorus	9	5.8±2.44	4.3±2.67	1.9±0.72
Pittosporum crassifolium	14	4.4±1.69	3.3±0.56	2.3±0.75
		Massey University		
Coprosma robusta	6	3.2±0.75	3.7±0.66	1.5±0.64
Melicytus ramiflorus	8	4.1±1.46	3.2±1.86	1.9±0.85
Pittosporum crassifolium	5	5.0±2.83	3.4±1.23	1.9±0.55
		All		
Coprosma robusta	18	3.6±1.09	3.7±1.29	1.7±0.74
Melicytus ramiflorus	17	5.0±2.15	3.8±2.32	1.9±0.76
Pittosporum crassifolium	19	4.3±1.98	3.4±1.45	2.2±0.70

Table 26. Statistical significance variables used in estimation of shrub foliage, branch, stem and aboveground biomass.

Variable	Foliage	Stem	Branch	Above ground
ln *D*	***	***	***	***
ln *H*	ns	***	***	***
Species	**	*	ns	**
Site	ns	ns	***	ns
Site*Species	ns	ns	ns	ns
ln *D**Site	ns	ns	*	ns
ln *D**Species	ns	**	ns	ns
ln *H**Species	ns	ns	ns	ns
ln *H**Site	ns	ns	ns	ns

Variables and their interaction used to estimate biomass indicated with *** has a $p<0.001$, ** $p<0.01$, * $p<0.05$ and ns not significant at $p<0.05$. ln denotes natural logarithms.

6.4.3. Species and site effects on shrub biomass

Stem component biomass was the highest overall for all the shrubs, contributing 47.6, 48.6 and 44.9%, followed by foliage biomass which contributed 33.4, 23.4 and 27.3% of the *ABM* for *C. robusta, M. ramiflorus* and *P. crassifolium*, respectively. The back-transformed means and standard errors for shrub species biomass variables are shown in Table 27.

Table 27. Back transformed foliage, stem and branch and total aboveground biomass (ABM) (kg+ SE) among native shrub species (*C. robusta, M. ramiflorus* and *P. crassifolium*) and between sites (Limestone Down and Massey University)

	Foliage	SE	Stem	SE	Branch	SE	ABM	SE
Species								
Coprosma robusta	0.164^{a}	0.023	0.228	0.025	0.076^{b}	0.015	0.477	0.052
Melicytus ramiflorus	0.087^{b}	0.012	0.210	0.019	0.118^{ab}	0.019	0.442	0.041
Pittosporum crassifolium	0.157^{ab}	0.023	0.256	0.035	0.232^{a}	0.056	0.655	0.090
Site								
Coprosma robusta								
Limestone Down	0.139	0.022	0.238	0.026	0.161^{1}	0.032	0.526	0.059
Massey University	0.181	0.042	0.217	0.039	0.036^{3}	0.012	0.433	0.079
Melicytus ramiflorus								
Limestone Down	0.075	0.014	0.220	0.029	0.258^{1}	0.059	0.490	0.064
Massey University	0.103	0.021	0.200	0.027	0.054^{23}	0.013	0.399	0.055
Pittosporum crassifolium								
Limestone Down	0.234	0.035	0.287	0.053	0.346^{1}	0.113	0.771	0.143
Massey University	0.130	0.032	0.228	0.039	0.156^{123}	0.047	0.556	0.096

Letters for biomass variable for species in a column differ significantly at $p<0.05$. Numbers for biomass variables for sites in a column differ significantly at $p<0.05$

Shrub species did not differ ($p>0.05$) in *ABM* and stem biomass. However, foliage biomass was higher ($p<0.05$) for *C. robusta* and branch biomass was higher ($p<0.05$) for *P. crassifolium* than in other shrubs. Site had no effect ($p>0.05$) on shrub biomass variables except branch biomass, which was higher ($p<0.05$) at Limestone Downs than Massey University.

6.4.4. Estimated parameters for shrubs biomass allometric models.

A summary of the best models for biomass variables, estimated parameters, model fit statistics, and correction factors across the model groups are shown in Table 28. The tested allometric functions varied in parameters (*a* and *b*) estimates and model fit statistics (AIC, RMSE and Adjusted R^2) across the model groups. However, the univariate *D* function was the best predictor for foliage biomass in all the model groups except for *P. crassifolium* where *BA*H* was marginally better. Stem biomass and *ABM* were predicted best by the derived *BA*H* function for all the model groups except for *C. robusta* and Massey University site models, where the bivariate function containing *D* and *H* performed slightly better. Species-specific models had the best fit for all the biomass variables, followed by the site-specific models. However, the Massey University foliage model explained the least variability (low Adjusted R^2) in contrast to all the other models.

The estimated *a* parameter was lowest and *b* highest for foliage biomass compared to both stem biomass and *ABM* across the model groups. This resulted in exponential growth ($b>0$) curves for foliage biomass (Figure 24) and exponential decay ($b<0$) curves for stem biomass and *ABM* (Figure 25 and 26) for all the model groups, except for *P. crassifolium* stem that had an exponential growth curve. Predicted foliage biomass rate of increase was greater in Limestone Downs and highest for *C. robusta* with increase in *D* for the site- and species-specific models, respectively.

Table 28. Parameters (*a* and *b*) estimate for predicting native shrubs foliage [ln(foliage)= ln(*a*)+*b**ln(*D*)], stem and aboveground (ABM) [ln(stem or ABM)= ln(*a*)+*b**ln(*BA*H*)] biomass (kg) for the best generalized, site-specific and species-specific models and their fit diagnostics (AIC, Adjusted R² and RMSE) and correction factor (CF)

Models	*a*	*b*	AIC	Adj R Square	RMSE	CF
Generalized models						
Foliage	-4.33	1.97	118.4	0.66	0.57	1.05
Stem	-3.78	0.88	63.79	0.89	0.40	1.01
ABM	-2.79	0.81	62.34	0.87	0.39	1.01
Site-specific models						
Foliage						
Limestone Down	-4.45	2.09	81.20	0.71	0.62	1.07
Massey University	-3.90	1.55	41.14	0.46	0.45	1.02
Stem						
Limestone Down	-3.70	0.86	46.55	0.88	0.42	1.02
Massey University	-3.94	0.92	21.37	0.88	0.36	1.01
ABM						
Limestone Down	-2.66	0.79	43.28	0.88	0.40	1.01
Massey University	-2.99	0.83	20.59	0.87	0.35	1.01
Species-specific models						
Foliage						
Coprosma robusta	-4.78	2.40	28.73	0.79	0.43	1.02
Melicytus ramiflorus	-4.31	1.57	40.02	0.61	0.56	1.05
Pittosporum crassifolium	-4.31	2.25	41.13	0.76	0.57	1.05
Stem						
Coprosma robusta	-3.29	0.71	9.55	0.90	0.89	1.38
Melicytus ramiflorus	-3.77	0.82	31.64	0.84	0.50	1.03
Pittosporum crassifolium	-4.17	1.07	-1.15	0.98	0.21	1.00
ABM						
Coprosma robusta	-2.51	0.71	15.33	0.86	0.31	1.00
Melicytus ramiflorus	-2.91	0.78	30.09	0.84	0.48	1.03
Pittosporum crassifolium	-2.88	0.91	6.35	0.96	0.25	1.00

The most accurate model should have both low AIC, RMSE, CF and a high Adjusted R²d

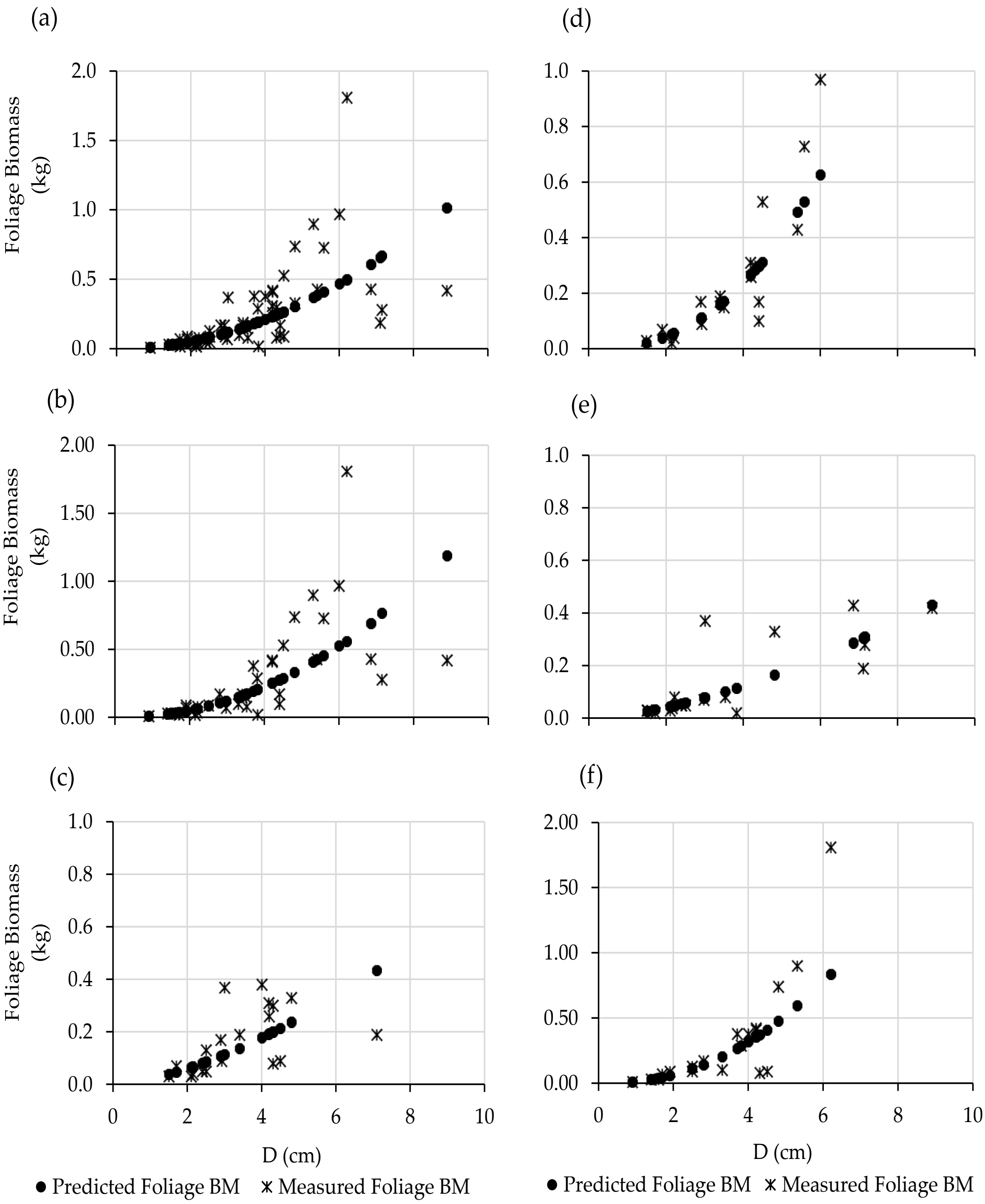

Figure 24.Relationship between basal diameter (D) and measured and predicted biomass (kg) for the (a) generalized, (b) Limestone Downs, (c) Massey University, (d) *C. robusta*, (e) *M. ramiflorus* and (f) *P. crassifolium* models.

The rate of change for predicted stem biomass was higher for Massey University and was highest for *P. crassifolium* with increase in *BA*H* for site- and species-specific models, respectively.

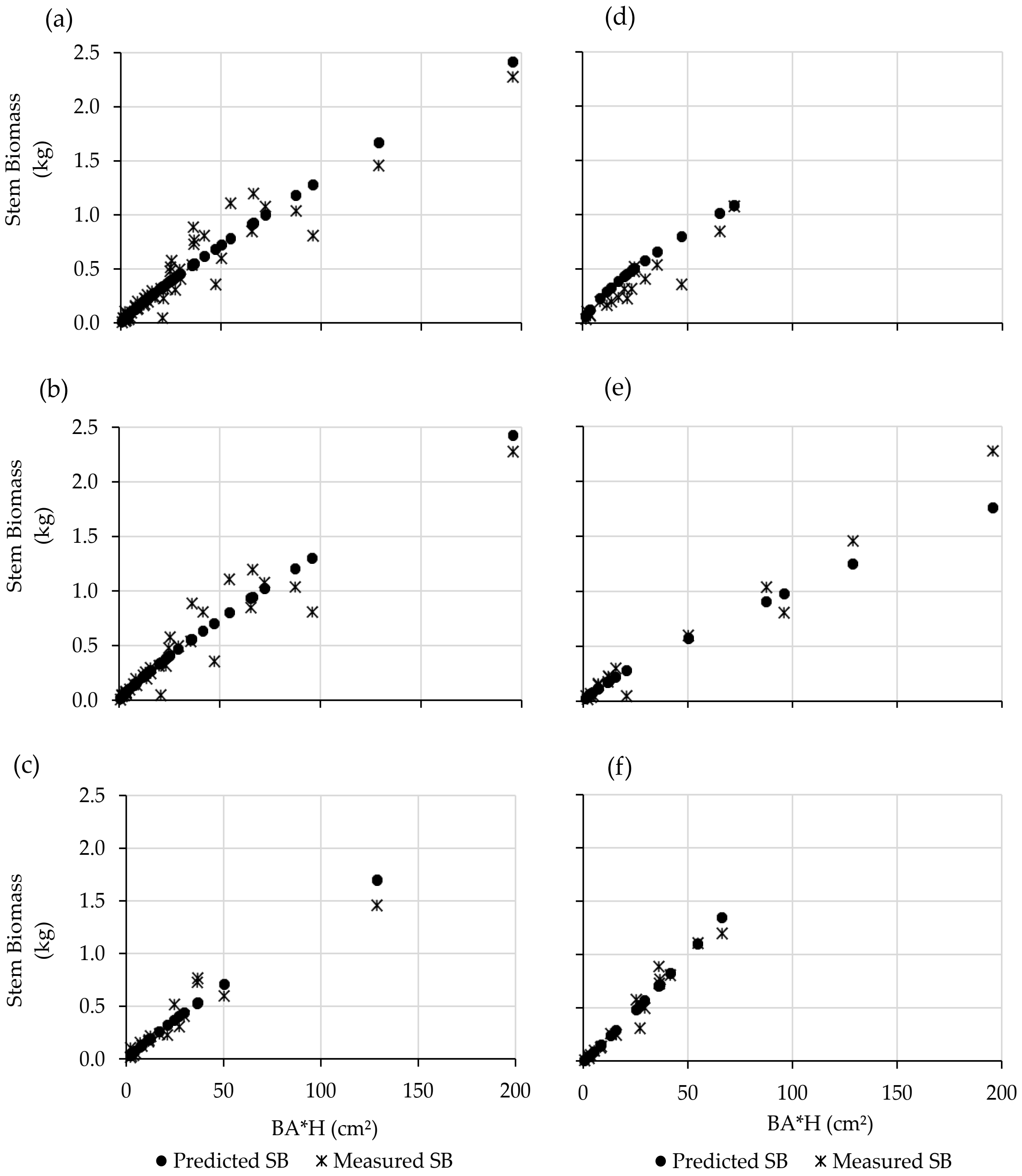

Figure 25. Relationship between stem volume (*BA*H*) and measured and predicted stem biomass (kg) for the (a) generalized, (b) Limestone Downs, (c) Massey University, (d) *C. robusta*, (e) *M. ramiflorus* and (f) *P. crassifolium* models.

There was marginal observable difference between the Limestone Downs and Massey University models with respect to the rate of increase for the predicted *ABM* with increase in *BA*H*. However, *P. crassifolium* had the highest and *C. robusta* the lowest rate of increase in predicted *ABM* with increase in *BA*H* among the species-specific models.

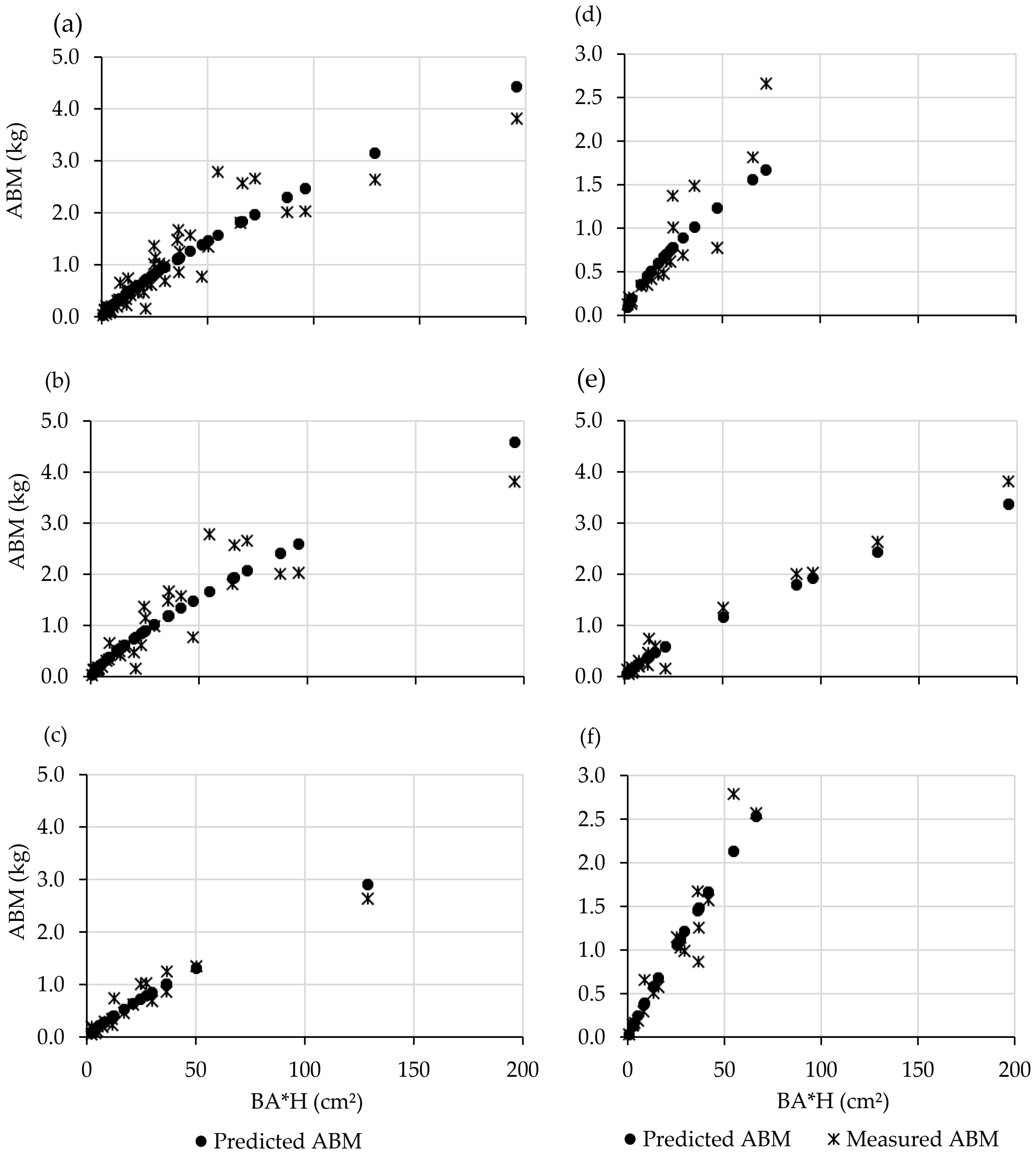

Figure 26. Relationship between stem volume (*BA*H*) and measured and predicted aboveground biomass (*ABM*) (kg) for the (a) generalized, (b) Limestone Downs, (c) Massey University, (d) *C. robusta*, (e) *M. ramiflorus* and (f) *P. crassifolium* models.

A comparison of the estimated parameters (*a* and *b*) for the best generalized model to both the site- and species-specific models is shown in Table 29. The parameters did not differ ($p>0.05$) among the models for foliage biomass and *ABM*. However, stem biomass parameters for *C. robusta* and *P. crassifolium* models were different ($p<0.05$) to those for the generalized model.

Table 29. *t*-test comparison of parameters (*a* and *b*) between the best generalized model and site- and species-specific models for native shrubs foliage [ln(foliage)= ln(*a*)+*b**ln(*D*)], stem and aboveground (ABM) [ln(stem or ABM)= ln(*a*)+*b**ln(*BA*H*)] biomass (kg)

	Foliage		Stem		ABM	
Model	*a*	*b*	*a*	*b*	*a*	*b*
Generalized	-4.3	2.0	-3.8	0.9	-2.8	0.8
		Site-specific				
Limestone Downs	-4.4	2.1	-3.7	0.9	-2.7	0.8
Massey University	-3.9	1.6	-3.9	0.9	-3.0	0.8
		Species-specific				
Coprosma robusta	-4.8	2.4	-3.3*	0.7*	-2.5	0.7
Melicytus ramiflorus	-4.3	1.6	-3.8	0.8	-2.9	0.8
Pittosporum crassifolium	-4.3	2.2	-4.2*	1.1*	-2.9	0.9

Parameters for site and species-specific models with asterisk (*) differ significantly at $p< 0.05$ with generalized model

6.4.5. Estimated Shrub Carbon Stock

The predicted cumulative CO_2 stock over 50 years for the native shrubs using the generalized model was 298.1 t CO_2/ha. This was 0.6 and 6.6% higher than predicted by the best Limestone Downs and Massey University models, respectively (Figure 27a). Among the species-specific models, *P. crassifolium* had the highest (532.1 t CO_2/ha) cumulative CO_2 stock over 50 years which was 60.0 and 62.8% higher than for *M. ramiflorus* and *C. robusta*, respectively (Figure 27b).

Mean annual CO_2 stock increment (MAI) for the generalized model was 6.0t CO_2/ha/y and was marginally higher than that for Limestone Downs (5.9 t CO_2/ha/y) and Massey University (5.6 t CO_2/ha/y) models over the 50 years. Comparing species-specific models, MAI was highest for *P. crassifolium* (10.6 t CO_2/ha/y) followed by *M. ramiflorus* (4.4 t CO_2/ha/y) and lowest for *C. robusta* (4.0 t CO_2/ha/y). Current annual CO_2 stock increment (CAI) increased exponentially and peaked after 7 years for all models except for *P. crassifolium* that occurred after 8 years, before decreasing exponentially. The peak CAI for the generalized model and Limestone Downs models was 1.9 t CO_2/ha and was higher than that for the Massey University model (1.7 t CO_2/ha). *Pittosporum crassifolium* model had the highest CAI of 3.0 t CO_2/ha, followed by *M. ramiflorus* (1.5 t CO_2/ha) and lowest for *C. robusta* model (1.4 t CO_2/ha).

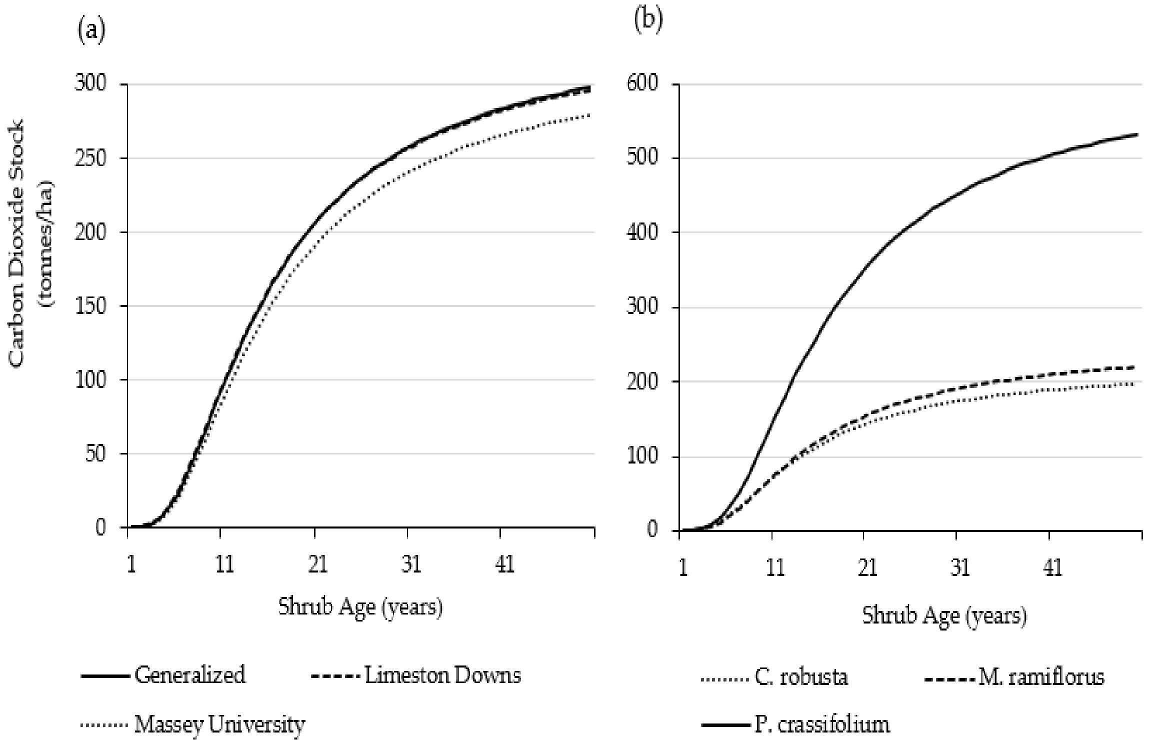

Figure 27. Native shrubs carbon dioxide (CO_2) stocks per hectare predicted using (a) generalized and site-specific (Limestone Downs and Massey University) models and (b) species-specific (*Coprosma robusta, Melicytus ramiflorus* and *Pittosporum crassifolium*) models using 8,000 stems per hectare.

6.5. Discussion

Clearing of native vegetation from hill country exposes the slopes to the potential for slip erosion and soil mass movement (Marden, 2018b). The major effects of this erosion includes loss of productive top soil, waterway pollution, increased greenhouse gases emission and loss of biodiversity (Ministry for the Environment & Stats NZ, 2019). Traditional tree/ shrub based biological erosion control measures on these farms have involved planting of exotic trees and shrubs such as poplar, willow, and radiata pine (McIvor, 2012). Poplar and willows have an added potential on the farm in that they can provide supplementary fodder, but they are deciduous (Kemp, 2001; New Zealand Poplar and Willow Research Trust, 2013). Although radiata pine produces marketable logs, harvesting on the steep slopes predisposes the land to erosion (Lambie, 2018). New Zealand native shrubs are genetically diverse and some are known to be palatable and browsed by wild herbivores (Bee, 2011). These shrubs can also be planted on steep slopes for erosion control, forage and in addition increase carbon sequestration and support native biodiversity conservation (Kimberley, 2014). Unlike the exotic species option, which have been widely studied, there is scant information on native shrubs biomass accumulation and carbon sequestration (Kimberley, 2021). Therefore, it is of benefit to estimate the native shrubs biomass yield and develop allometric functions for biomass and carbon stock estimation. This information will be essential for estimation of fodder availability and in determination of carbon stock for emission trading, if native shrubs are planted on hill country sheep and beef farms.

6.5.1. Native shrubs biomass

Different sites can vary in ambient conditions, topography, and soil properties, which can affect plant growth and biomass accumulation (Poorter, 2015). Biomass partitioning in plants including woody vegetation changes with age and in response to changing ambient and soil conditions (Poorter & Sack, 2012b; Marden, 2018b). Although woody plant species respond to changes in these conditions differently, they have similar patterns of biomass allocation (Poorter, 2012b). The result of the study by Poorter (2012b) showed that constraints in environmental condition induces woody plants to invest biomass to the aboveground components while limitations in the soil resources stimulates biomass allocation to the root system (Poorter, 2012b). There were no differences in *ABM* accumulation and biomass allocation to different shrub components except for branches. The *ABM* similarity between sites could be due to the age (<8 years) of the shrubs examined, which had small basal stem diameters (<10 cm). However, the differences in branch biomass between sites may be due to differences in plant density between the sites (Poorter, 2012a, 2015). Plant density can affect the light received by plants thereby influencing their branching mechanism (Leduc et al., 2014). Tall plants in high density vegetation with mixed plant sizes can cause shading of younger and shorter plants inducing branch suppression and therefore reduced biomass allocation to the branches (Leyser, 2009; Poorter, 2012a; Leduc, 2014). Shrubs at Limestone Downs had higher branch biomass suggesting the plant density was lower than for those in Massey University. Although this was not measured. However, plants maintain a functional biomass equilibrium to compensate for changes in biomass allocation in the various plant parts in response to environmental stresses (Poorter, 2012b). Consequently, native shrubs in Limestone Downs had lower foliage to branch biomass ratio as compared to those at Massey University.

There are few studies that have estimated biomass of native woody vegetation in New Zealand (Scott, 2000; Marden, 2018b). These studies have focused on native shrubs and trees intended for erosion control and timber production and hence their emphasise has been more on root biomass (Watson & O'Loughlin, 1985; Marden, 2005b; Marden & Lambie, 2015; Marden, 2018b). Native shrub species in this study showed no difference in *ABM* accumulation. The *ABM* for the native shrub species examined were greater than reported for juvenile *Leptospermum scoparium* (Mānuka) (Marden, 2015) but, lower than reported for young native trees in New Zealand (Marden, 2018b). Although the native plants in these studies were of different genera, the difference in biomass accumulation can be attributed to their contrasting environments. Native young trees reported by (Marden, 2015, 2018b) were grown in experimental plots while native shrubs in this study were sourced from natural stands.

Stem biomass accounted for the highest proportion of *ABM* for the native shrub species in this study, similar to other research with woody vegetation (Ketterings, 2001; Istrefi et al., 2019) and young native trees species in New Zealand (Marden, 2018b). Young woody plants divert a higher proportion of biomass to the stems for support and elongation (Marden, 2018b) and is heightened by increase in plant density (Poorter, 2012a). Stem biomass for the native shrubs in this study was similar to that reported for young (<5 years) native tree species in New Zealand (Marden, 2018b).

Foliage and branch biomass were the most variable biomass components because they are more dependent on the plant architecture and morphology and are influenced by plant genotype and ambient environment (Poorter, 2012a; Marden, 2018b). Plants exhibit architectural and morphological plasticity based on the abiotic resources niche they have evolved in and have adapted to occupy (Ford, 2014). In natural vegetation, *C. robusta* is mostly found in open canopy areas where it assumes a spreading morphology (de Lange, 2022a). Shrubs with spreading growth form have greater area for leaf growth hence more foliage biomass. Conversely, *M. ramiflorus* and *P. crassifolium* are mainly found naturally in native forest sub-canopy zones and have adapted to limited space and light through erect morphologies (de Lange, 2022d, 2022c). Erect shrubs invest biomass in branches to increase the area for leaf growth. Unlike *M. ramiflorus* that has spreading branches (Salmon, 1996; de Lange, 2022c), *P. crassifolium* can assume fastigiate branches making it more versatile in space limited environments (Salmon, 1996; Metcalf, 2011). Foliage biomass was similar for *C. robusta* and *P. crassifolium* suggesting the two species can be comparable for fodder yield if planted on a farm. Further, *P. crassifolium* had greater branch biomass than the other two shrubs indicating the species adaptability to high plant density. Comparably, more *ABM* was allocated to branches for *M. ramiflorus* and *P. crassifolium* and to foliage for *C. robusta*. Higher *ABM* allocation to branches was reported by (Marden, 2018b) for juvenile native trees species in New Zealand.

6.5.2. Allometry functions for native shrubs biomass

Plant biomass allometry depends on genotype and environment interactions because they affect the size, architecture and morphology of the whole plant and its components (Poorter, 2015). In contrast, shrubs differ from trees in architecture and morphology by having multiple stems and are lower in height (Götmark et al., 2016). The multi-stemmed nature of shrubs makes their morphology and architecture highly variable with age and across sites compared to trees (Yao et al., 2021). Allometric functions using single measurements of stem diameter or height can give highly accurate predictions of *ABM* and component biomass for trees, but may result in low accuracy for shrubs because of their variable morphology and architecture (He, 2018; Yao, 2021). In this study, allometric functions combining both *D* and *H* performed better than univariate functions in estimation of *ABM* and stem biomass, which is in agreement with earlier studies (Ali, 2015; Flade, 2020; Nyamjav, 2020). However, allometric functions using derived stem volume (*BA*H*) were superior in estimation of *ABM* and stem biomass than those combining both *D* and *H*. Allometric functions using derived parameters such as area and volume increased accuracy of woody biomass estimation because they consider the shape of a shrub (Beets, 2012; Flade, 2020; Yao, 2021). Conversely, foliage biomass was predicted better by *D* univariate allometric functions. This would be expected because there is a high correlation between stem diameter and leaf biomass in woody plants (Poorter, 2012a; Sun et al., 2019).

The *cBM* and *ABM* were predicted more accurately by species-specific allometric functions and followed by the site-specific functions. Similar observations are reported in other studies for tree and shrub species (Ali, 2015; He, 2018; Marden, 2018b; Nyamjav, 2020). The higher accuracy of the species-specific allometric functions can be expected because of species conformity in biomass accumulation and allocation to the shrub components (Poorter, 2015). Further, a greater accuracy for the site-specific allometric functions can be expected because sampled shrubs were exposed to similar abiotic conditions at each site (Poorter, 2015). However, the site-specific allometric function for foliage biomass at Massey University showed greater variability between the measured and predicted biomass. The high variability arose because a greater proportion of sampled shrubs at Massey University were from the nature reserves and a smaller proportion was obtained from experimental plots. Shrubs in the trial sites were at relatively low density compared to the nature reserves and this explains why they could have had more foliage biomass. Comparison of the species-specific and site-specific allometric functions to the generalized allometric function showed no differences in *ABM* and foliage biomass. This indicates that the generalized allometric functions are sufficient to predict *ABM* and foliage biomass for native shrubs in natural stands or plantations of mixed species under high density. Generalized allometric functions have been found to be sufficient for estimating shrub biomass in other studies (He, 2018). In addition, the generalized allometric functions can be used to estimate stem biomass for *M. ramiflorus*, but species-specific allometric functions would be needed for *C. robusta* and *P. crassifolium*.

6.5.3. Native shrubs carbon sequestration

The CO_2 cycle in plants involves shifts between respiration and photosynthetic carbon accumulation to transient and enduring tissues in the above and below ground biomass components (Jansson et al., 2021). Biomass accumulation and hence carbon sequestration can vary among woody plant species due to the differences in growth rate and longevity (Bernal et al., 2018; Burrows et al., 2018). However, carbon sequestration per unit area is finite and depends on the photosynthetic capacity of plants to accumulate biomass (Burrows, 2018). Additionally, differences in abiotic conditions across sites can influences the plants biomass accumulation capacity (Poorter, 2015; Ministry for Primary Industries, 2017). The effect of species and abiotic factors across site on carbon sequestration for New Zealand forest vegetation have been extensively studied (Beets, 2012; Kimberley, 2014; Ministry for Primary Industries, 2017; Burrows, 2018; Carswell et al., 2019). Comparably, New Zealand exotic and native forest trees have superior carbon sequestration capacity than the natives shrub, because of their greater growth rates (Ministry for Primary Industries, 2017).

New Zealand native shrubs are diverse and can vary in their carbon sequestration capacity (Kimberley, 2014, 2021; Schwendenmann, 2014; Marden, 2015). In this study, *P. crassifolium* had the highest, while *M. ramiflorus* and *C. robusta* the least estimated sequestered carbon dioxide. This agrees with findings by (Schwendenmann, 2014) for the same species. Compared to the other two native shrubs in this study, *P. crassifolium* had nearly twice the MAI (mean annual increment) and CAI (current annual increment) carbon stock, indicating it can offer superior carbon sequestration when planted on farm. The carbon stock MAI and CAI for the shrubs in this study were higher than for *L.*

scoparium (Mānuka) (Marden, 2015; Carswell, 2019) but within the range reported for other native shrubs (Beets, 2014b; Schwendenmann, 2014; Carver, 2017; Kimberley, 2021) and less than for New Zealand native trees (Kimberley, 2014).

Carbon sequestration predicted using the generalised allometric function was lower than estimated by (Ministry for Primary Industries, 2017) and can be attributed to the differences in native shrubs and sampling sites used in the studies. The estimates from the Ministry for Primary Industries (2017) were from naturally regenerating kanuka/Manuka shrubland (Kimberley, 2021). This suggests that generalised allometric function determined in this study could be utilized to estimate the average carbon stock for a mixed native shrub species in either nature reserves or planted in high density on farm. Estimates for carbon sequestration using the generalised allometric function were comparable to the site-specific functions. This indicates that a generalised allometric function could be extended to predict average carbon stock for a mixed native shrub species for sites containing abiotic conditions similar to the present study sites. However, there were greater discrepancies in estimated cumulative carbon stocks between the generalised and species-specific allometric functions and would be expected because carbon sequestration is species-specific (Kimberley, 2014, 2021). Therefore, species-specific allometric functions generated in this study should be restricted to respective species growing under abiotic conditions similar to the study sites.

6.6. Conclusion

This study sought to estimate the native shrubs foliage, stem, branch components biomass and aboveground biomass, thereafter, develop and compare the species, site, and generalized allometric functions predicting biomass variables, then use the best model to estimate native shrubs' carbon stock. The findings showed that the native shrubs used in this study had similar stem and aboveground biomass. However, *Coprosma robusta* and *Pittosporum crassifolium* had more foliage than *Melicytus ramiflorus* and therefore can supply more fodder if planted on farm. The species-specific allometric functions had greater accuracy in estimating native shrubs components (stem and foliage) and aboveground biomass. However, the generalised allometric functions were comparable to the species-specific allometric functions for foliage and aboveground biomass. Therefore, the generalised functions can be used to estimate the foliage and aboveground biomass for the native shrubs in New Zealand growing under similar conditions to those of the study sites. Prediction of carbon stock over 50 years using the species-specific allometric function showed that *Pittosporum crassifolium* had greater rate of carbon stock accumulation and sequestered more than twice carbon compared to the other two native shrubs. The findings show that a mixed native shrub species planted on farm can have greater benefits as the different species would complement each other for foliage production and carbon sequestration. However, the findings in this study are premised on young native shrubs and therefore acknowledges that biomass variables, allometric functions and carbon stock estimates will likely change as the shrubs age.

Forward to Chapter 7

Some of the data gaps related to native shrubs, identified in Chapter 3, have been addressed in Chapters 4, 5, and 6. Chapter 7 utilized this new data to update the NSM sub-model. Additionally, a radiata pine sub-model was developed and integrated into the bioeconomic model to allow for a comparison of the use of native shrubs versus radiata pine on hill country farm steep slopes.

Chapter 7: Bioeconomic System Dynamics Modelling to Compare Native Shrubs and Radiata Pine as Alternative Land Use Options on Marginal Portions of Hill Country Farms in New Zealand

Abstract

Native shrubs and radiata pine are among afforestation species option for the steep slopes on hill country sheep and beef farms. However, there has not been a simulated comparison of native shrubs and radiata pine as alternative land uses on these farms because of limited native shrubs data. A bioeconomic system dynamic model containing a native shrub sub-model was used in chapter 3 but was based on limited native shrubs literature data. Therefore, the purpose of this study was to update the native shrubs sub-model with new research data and to develop a radiata pine sub-model as a comparison for integration into the bioeconomic model. Thereafter, use the combined model to assess the impact on farm feed supply, sheep flock dynamics and farm economics of using either native shrubs or radiata pine on the farm steep slopes. Planting native shrubs caused a 6.5% and 7.0% and radiata pine 7.0% and 7.4% decrease in farm feed supply at 10% and 20% planting rates, respectively. Decrease in farm feed supply led to a reduction in flock size of 8.8% and 11.4% with native shrubs and 10.0% and 12.1% with radiata pine at 10% and 20% planting rates, respectively. Reduction in flock size caused a decrease in number of lambs sold and therefore the sheep flock net cashflow. Radiata pine had surplus net cashflow that compensated and exceeded the reduced sheep flock net cashflow resulting in higher sheep enterprise cash operating surplus than the base scenario. Conversely, native shrubs had a negative cashflow and combined with reduced sheep flock net cashflow led to lower sheep enterprise cash operating surplus than the base scenario. The estimated break-even carbon price required to make utilization of native shrubs to be similar to the base scenario was 85.0 NZ$/NZU and 147.2 NZ$/NZU for the best- and worst-case scenarios, respectively tested in this study. In conclusion, native shrubs are potential alternative land use on hill country farms steep slopes, but policy intervention to lower seedling costs and making carbon income comparable to that of radiata pine is needed to make them profitable and attractive investment on the farms.

Keywords: Bioeconomic modelling; native shrubs; radiata pine; cash operating surplus; hill country sheep and beef

7.1. Introduction

The expansion of sheep and beef farms in New Zealand over the last 180 years (Allen, 2013) led to increased productivity and profitability of the farming enterprise, but has also resulted in negative environmental effects due to the clearance of native vegetation for temperate perennial pasture production (Allen, 2013). The negative environmental effects of the expansion included rise in greenhouse gas emissions, loss of biodiversity, increased waterway pollution, and soil mass movement (Ministry for the Environment, 2022). However, soil mass movement is of greater significance on hill country because it predisposes the land to the other negative environmental effects in addition to causing destruction to properties (Basher, 2013). Soil mass movement is more pronounced on the steeper slopes where clearing of deep-rooted woody vegetation caused soil instability and subsequent vulnerability to erosion (Basher, 2013). Biological soil conservation efforts on hill country farms have mainly focused on utilization of the extensively studied exotic tree and shrub species such as spaced poplar and willow, and radiata pine plantation (Hocking, 2003; McIvor, 2011; Basher, 2013). However, there is increasing interest in the utilization of native woody species as alternative land use on steep slopes (Pollock, 1986; Phillips, 2015a), but information on how they compare to the exotic species is scant.

Compared to other exotic tree and shrub species used for soil conservation on hill country sheep and beef farms, radiata pine is widely utilized because of its fast growth rate, broad site tolerance, and higher economic returns through sale of logs (Wilkinson, 1999; Hocking, 2003; Satchell, 2018). The fast growth rate of radiata pine makes it superior for carbon sequestration (Ministry for Primary Industries, 2017) and in stabilizing soil on the steep slope (Hocking, 2003). Additionally, radiata pine has shorter harvesting rotation which makes it the dominant forestry species accounting for over 90% of log production in New Zealand (Hocking, 2003). However, the monocultural nature of radiata pine plantations reduces biodiversity and the short harvesting rotations exposes the steep slopes to cyclic vulnerability to soil mass movement (Phillips, 2015a). This can increase the storm induced risk of slash (wood debris) washing to the waterways post harvesting, which can cause significant damage to properties, infrastructure, environment, and the aquatic ecosystem (Phillips, 2015a; Satchell, 2018). In addition, radiata pine roots decay rapidly after tree harvesting which reduces soil stability and increases the risk of soil mass movement on the steep slopes (Phillips, 2015a; Satchell, 2018).

An earlier simulation modelling study results (Chapter 3) showed that utilization of native shrubs as an alternative land use to pasture on hill country farms steep slopes can be economically viable at carbon prices above 56 NZ$/NZU. 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 (Chapter 3). However, the native shrubs sub-model was based on limited literature data (Chapter 3). Therefore, the objectives of this chapter were to (i) update the native shrubs sub-model using new research findings on native shrubs (Chapter 4, 5 and 6), (ii) develop a radiata pine sub-model and integrate it to the model to allow for comparison of radiata pine to the native shrubs as alternative land use options to pastures on hill country farms, and (iii) use the improved model to compare the impacts on (a) farm feed supply, (b) sheep flock dynamics and (c) farm economics, of asynchronous use of either native shrubs or radiata pine as alternative land use to pastures on 10% of farm effective area on the steep slope portion.

7.2. Methods

7.2.1. Model development and structure

A Radiata Pine subsystem Model (RPM) was developed in STELLA Architect version 1.9.3 (version 2019, isee systems, Lebanon, NH, USA) and added to the New Zealand North Island hill country sheep and beef farm model (HCM) (Farrell, 2019), which was previously improved to include a Native Shrubs subsystem Model (NSM) (Chapter 3) (figure 28). The HCM was organized into modules representing sheep flock, beef cattle herd, pasture feed utilization, wool production and farm economics (Farrell, 2019). Simulations of HCM have been used previously to assess the impacts on productivity and profitability of hill country sheep and beef farms due to sheep wastage rates (Farrell, 2019), sheep flock replacements (Farrell, 2020b, 2020a), sheep breeding strategies and beef herd management (Farrell, 2020d; Farrell et al., 2020c; Farrell, 2021b). The addition of NSM to HCM allowed for partitioning of 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 modules (Chapter 3). System dynamics of HCM and NSM are detailed in (Farrell, 2019, 2020) and Chapter 3, respectively.

The NSM assumed that native shrubs were the only alternative to pastures in steep slopes utilization (Chapter 3). However, other trees and shrub species can also be planted on the steep slope for wood production (Hocking, 2003; Satchell, 2018) and erosion control (Wall et al., 1997; Douglas, 2009; Eyles, 2010; Phillips, 2012; Basher, 2013). Among the alternative to native shrubs is radiata pine (Satchell, 2018). Therefore, the RPM was developed to allow for asynchronous use of native shrubs and radiata pine on the steep slope portion of the farm. The RPM consisted of radiata pine growth, wood production, carbon stock and radiata pine economics modules.

The base 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 the sale of logs. Additionally, area planted in native shrubs was assumed to contribute browse fodder and understorey pastures to the farm feed supply during the browsing period.

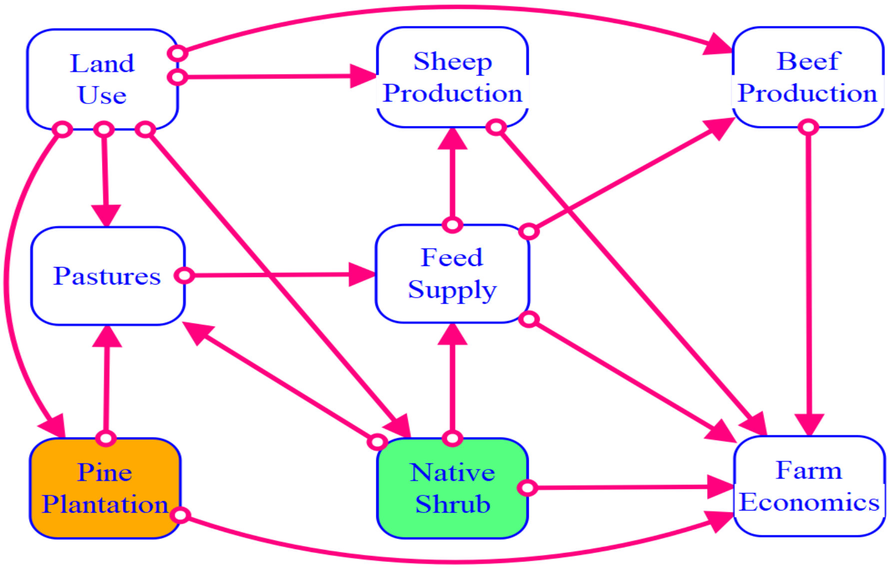

Figure 28. Schematic diagram of the modules of hill country sheep and beef farm model (HCM) (white fill) [1], native shrub (NSM) subsystem model (green fill) [2] and the radiata pine subsystem model (brown fill). The arrows show the direction of interaction among the modules and subsystem models.

7.2.2. 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, 2019) previous simulations and (Chapter 3). In addition, this region accounts for approximately 50% of the North Island sheep population (Beef+lamb NZ, 2021, 2022), has greater proportion of steep slopes (Murray, 1999; Marden, 2012, 2018a) 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, 2022), of which approximately 50% is steep slopes (Murray, 1999; Saggar, 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 (Chapter 3). The slope classes proportions were within the ranges used for the East Coast region hill country farms (Page, 1988; Murray, 1999; Saggar, 2015).

Studies on hill country farms have often used different slopes elevations to classify the slope classes (Hodgson, 2005; Saggar, 2015; Kemp, 2016; Beef+Lamb NZ, 2020b). However, the model adapted elevation of <12° for flat, 13 to 25° medium and >25° for steep slope (Murray, 1999; López, 2003) to reflect the slopes critical to pasture production (Lynn, 2009). Slope classes differ in soil properties and microclimate, which affects pastures yield and quality (López, 2003). Flat areas on hill country farms have higher pasture production and quality and reduces with increasing slope elevation (López, 2003; Kemp, 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 (Hodgson, 2005; Lynn, 2009; Beef+Lamb NZ, 2022). A SU in New Zealand represents the annual feed a 55 kg ewe rearing a single lamb to weaning at 28 kg requires (Lynn, 2009).

7.2.3. Sheep flock and beef herd dynamics

The current model retained the livestock classes and structure in HCM (Farrell, 2019) and the sheep flock dynamics in Chapter 3. Similar to earlier simulations using HCM (Farrell, 2019, 2020a, 2020b, 2020c, 2021a, 2020) and Chapter 3, the beef cattle herd was held constant and allocated 40% of the farm feed supply (Beef+Lamb NZ, 2022). However, the sheep flock fluctuated in response to feed supply dynamics caused by land use changes on the farm steep slope (Chapter 3). Changes in land use from pastures 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 (Chapter 3) with no external sourcing of feed and replacement flock (Farrell, 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 (Chapter 3). Sheep flock management on reproduction, culling and deaths for all age groups (Farrell, 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 to 2021 (Beef+Lamb NZ, 2022).

7.2.4. 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 utilization. Flat and medium slopes were entirely used for pastures production. However, the steep slope was divided into pastures and afforestation land use areas. The afforestation area was equal to 10% of the entire effective farm area (62.4 ha) and was planted with either native shrubs or radiata pine, while the remaining non-afforested steep area was left in pastures. Because pastures yield and quality vary across slope classes (Lambert, 2014; Kemp, 2016), the monthly pasture production and quality for East Coast region (Trafford, 2011) was used as the average for the flat land. Pasture production for the medium and steep slopes were calibrated to be approximately 52.6% and 38.6% of the flat land production. The calibrated pasture production for the slope classes were within the reported range for North Island and the East Coast region (López, 2003; Lambert, 2014; Kemp, 2016).

7.2.5. Management of the afforestation site

Prior to planting with either native shrubs or radiata pines, the steep slopes contained unimproved pastures 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 mechanized methods on the steep slope (Maclaren, 1993). Wire fencing was carried out to demarcate the area for afforestation in each year and to control wild ungulates from damaging the seedlings and consuming the native shrubs.

Seedling were assumed to be sourced locally and transported to the planting site. Containerized and bare rooted seedlings were used for native shrubs (Cimino et al., 2014) and radiata pine (Maclaren, 1993), respectively. Seedlings were hand planted for both the native shrubs and radiata pine (Maclaren, 1993; Cimino, 2014). During planting, diammonium phosphate (DAP) fertilizer was applied (approximately 85g 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). All tools used for planting were supplied at the farm.

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.

7.2.6. Estimation of native shrubs growth

Plants growth exhibit a sigmoid growth curve and can be described using nonlinear mathematical functions (Paine, 2012). Gompertz function is the commonly used in estimating plants sigmoidal growth because it does not assume constant growth rate and the curve is radially asymmetrical (Paine, 2012). A Gompertz function (Equation 26) was used to estimate the native shrubs stem basal diameter growth over 50 years. The Gompertz function parameters were estimated by fitting the curve using the native shrubs basal diameters (Chapter 6). The shrubs in Chapter 6 were estimated to have an initial plant density of approximately 8,500 stems per hectare (sph). However, native shrubs can be planted for various purposes, which can affect the planting density with reports ranging from 1,000 to 10,000 sph in various studies (Pollock, 1986; Bergin, 2014; Cimino, 2014; Kimberley, 2014). Mixed native shrubs planted at high density (>10,000 sph) attain canopy closure early (average 3 years), while spaced planting (<1,000 spa) delays canopy closure (10 year <) (Pollock, 1986; Bergin, 2014). Planting density of approximately 2,500 sph (2m spacing) is recommended for native shrubs aimed for canopy closure approximately 10 years after planting (Bergin, 2014). An initial plant density of 2,000 sph was used in the model because it can ensure establishment of the native shrubs within 5 years (Bergin, 2014) and be browsed for five years prior to canopy closure at approximately 10 years after planting.

Growth rate in woody plants is affected by plant density due to competition for space, light and soil resources (Poorter, 2012a). Therefore, a calibration function was used to scale up the stem basal diameter for the native shrubs at 8,500 (Chapter 6) to approximately 2,000 sph. The calibration function (Equation 27) was derived by regressing stem diameters of *Eucalyptus saligna* (Eucalyptus) obtained from Nelder spacing data in New Zealand (McKenzie, 1996). The Eucalyptus data was used due to lack of similar data for New Zealand native shrubs.

Equation 26 $$D_i = \left[10.98 \times e^{\left(-e^{\left(-0.18\left(t_i - 4.95\right)\right)}\right)}\right] + d_{c_i}$$

Equation 27 $$d_{c_i} = -3.044 + (1.41 \times d_{f_i})$$

Where D_i was estimated native shrubs stem basal diameter at time t_i, $d_{c_i}$was calibration factor to scale stem basal diameter to equivalent native shrubs at 2,000 sph and d_{f_i} was native shrub stem basal diameter at 8,500 sph.

7.2.7. Estimation of native shrubs foliage yield and nutritional quality

Plant growth entails the simultaneous increase in the size of its parts (roots, stem, branches, leaves and reproductive tissues) and this relationship can be determined using allometric functions (Marden, 2018b). The allometric relationship between stem diameter and foliage yield is well established (Kemp, 2003; McAlpine, 2007; Poorter, 2012a, 2015; De Cáceres et al., 2019; Sun, 2019) and can be used to estimate fodder production in trees and shrubs (Kemp, 2003). However, plant growth rate is species specific and allometric functions can differ across genera (Poorter, 2012a). Nonetheless, generalized allometric functions for mixed shrub species using stem basal diameter have been shown to be satisfactory in estimation of foliage yield (Chapter 6) (Ali, 2015; He, 2018; Flade, 2020). Therefore, a generalized allometric function (Equation 1) for estimating the foliage yield using basal stem diameter of mixed native shrubs (Chapter 6) was used in the model. The allometric function was derived using three common native shrubs (*Coprosma robusta* (Karamū), *Pittosporum crassifolium* (Karo) and *Melicytus ramiflorus* (Māhoe)) sampled mainly from nature reserves in Waikato and Palmerston North districts in New Zealand (Chapter 6). In this study, foliage was assumed to be composed of leaves and soft branchlets less than 5 mm which are edible to sheep (Kemp, 2003).

Equation 28 $$F = e^{-4.3} + D^{e^{2.0}}$$

Where F was foliage yield (dry matter) and D native shrubs stem basal diameter

Foliage nutritional composition can vary among native shrub species and across the season (Chapter 4). Differences in nutritional composition among native shrub species can be attributed to phylogeny while across the season due to changes in weather and soil conditions (Chapter 4). Native shrub nutritional composition differences are more pronounced in leaves than in their edible stems (Chapter 4 and 5). In this model, sheep were assumed to browse both leaves and edible stem dry matter at equal proportions. Therefore, foliage quality was the average of the leaves and edible stems nutritional quality in terms of metabolizable energy (ME). Native shrubs monthly foliage quality (Figure 29) was estimated using the average seasonal ME of five native shrubs (*Coprosma robusta*, *Griselinia littoralis*, *Hoheria populnea*, *Pittosporum crassifolium* and *Pseudopanax arboreus*) (Chapter 4 and 5).

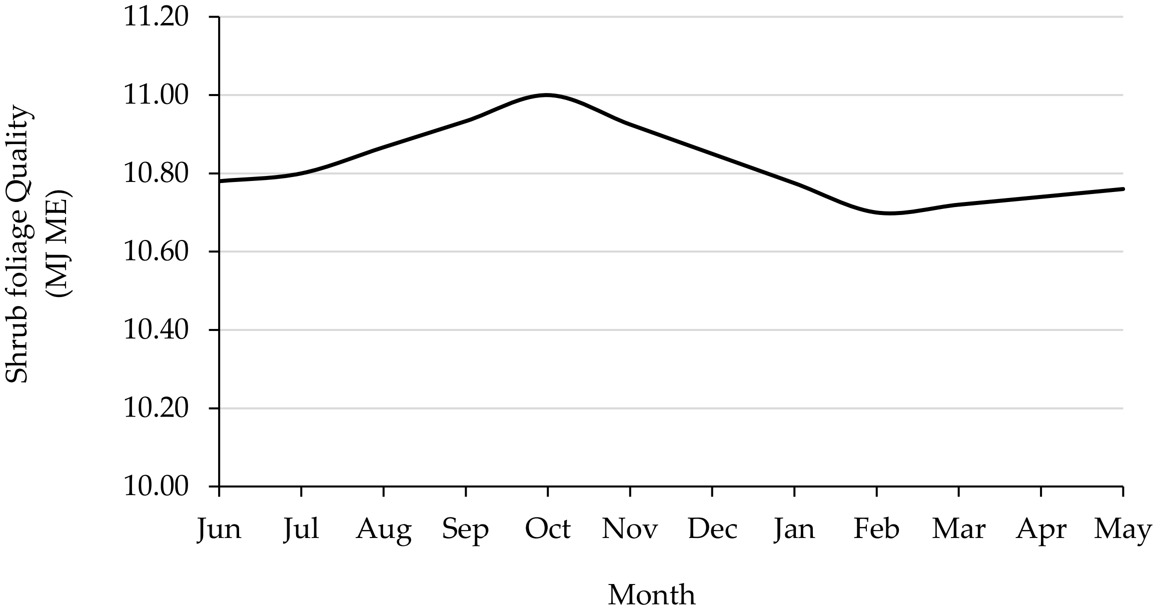

Figure 29. Estimated New Zealand native shrub monthly foliage quality in Mega Joules of metabolizable energy (ME MJ)

7.2.8. 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 metabolizable energy (MJ ME) (Chapter 3). Pasture supply was from open and understory pastures. 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 pastures were allocated to sheep and available only during the browsing period (summer season) for a period of five years. Allocation of native shrub fodder and understory pasture to sheep was because sheep can browse the shrubs with minimal damage and have lower trampling impact as 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, 2014; Marden, 2018b). 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 pastures growth (Benavides, 2009; Hussain, 2009; Bergin, 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, 2007). Sheep were assumed to browse native shrubs fully up to the height of approximately 0.9 m (Sanon, 2007; McEvoy, 2008) after which fodder access decreased logarithmically ceasing after 5 m (Chapter 3). Similarly, understory pastures growth rates decreased logarithmically with growth of native shrubs due to the shading effect (Chapter 3). The estimation of feed supply from afforested areas in native shrubs using NSM was retained (Chapter 3).

Feed demand was estimated based on sheep flock and beef cattle herd feed requirements for each year (Farrell, 2019). The difference between feed supply and demand was taken as the feed balance for the farm (Farrell, 2019) and was used to estimate sheep flock self-adjustments (Chapter 3).

7.2.9. 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 (Maclaren, 1993; Satchell, 2018) and therefore must be harvested for logs within 25 to 35 years of growth for it to be economically feasible (Maclaren, 1993; Satchell, 2018). In addition, the fast growth rate of radiata pine makes it superior in carbon sequestration compared to other tree and shrub species in New Zealand (Chapter 6) (Ministry for Primary Industries, 2017; Kimberley, 2021).

The RPM simulated radiata pine growth in terms of log production and carbon stock accumulation over a rotation length of 25 years (Maclaren, 1993). An initial planting density of 1,000 sph was used with the trees thinned to a final log production stand of approximately 500 sph (Maclaren, 1993; NZ Farm Forestry, 2007). Two non-production thinning were carried out in the 7th and 12th years of the rotation (Maclaren, 1993). To ensure the trees attained sellable log qualities, they were pruned in three lifts within the rotation period (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).

7.2.10. Carbon stock estimation

Plants sequester carbon dioxide from the atmosphere and photosynthetically convert the carbon element into biomass (Poorter, 2012a). Therefore, 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 native shrubs have not been documented (Kimberley, 2021), largely because of their wide genetic diversity (Salmon, 1996; Metcalf, 2011). Therefore, the generalized estimated values for an indigenous forest planted post 1989 (Ministry for Primary Industries, 2017) were used to simulate carbon stock accumulation for the native shrubs.

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 the 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).

7.2.11. Modelled farm economics.

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, 2019) and therefore the enterprise cashflow was unaffected by land use changes (Chapter 3). Cashflow for the sheep enterprise was dependent on the flock size and lamb sale policy, which were affected by feed supply. Therefore, the sheep enterprise cashflow was influenced by land use change on the steep slope, choice of afforestation species and planting rates. The cashflow for native shrubs and radiata pine was only affected by their 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 used to include scenarios of a lower and higher risk on investments, respectively due to uncertainty in future inflations (The Treasury, 2008). The assessment used discounted net cashflow in terms of cash operating surplus (COS), net present value (NPV), and break-even analysis economic tools (Chapter 3). The afforestation interventions were compared to a base scenario with pastures 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. Therefore, five simulations (pasture, NS10%, NS20%, RP10% and RP20%) outputs were used in the economic assessment.

Calculation for beef herd and sheep flock enterprises cashflow followed HCM (Farrell, 2019) while that for native shrubs enterprises followed NSM (Chapter 3). The income and expenses for HCM and NSM were updated to reflect the present production status in New Zealand East Coast region hill country sheep and beef farms (Beef+Lamb NZ, 2022). 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). Because of the steep nature of the afforested area, thinning, pruning, and logging costs were adjusted to be approximately 15% higher than would be on the easier slope classes (Askin & Askin, 2018). Carbon cash inflow was estimated using a three-year (2020 to 2022) average of carbon price per New Zealand Emission Unit (NZ$/NZU), which was 65.3 NZ$/NZU. Income from sale of logs was based on the average price over 12 quarters ending December 2022 for each class (pruned, A grade, K grade and pulp) of logs for export (Ministry for Primary Industries, 2023).

7.3. Results and Discussion

7.3.1. Overall farm feed supply

Annual farm feed supply with pastures on the steep slope was 25.9 million MJ ME and remained constant over the simulation period (50 years) (Figure 30). This was an 11.5% increase in total farm feed supply (23.23 million MJ ME) compared to the previous model (Chapter 3). The increase was due to 10.6% increase in the effective farm area in the current modelled farm (624 ha) (Beef+Lamb NZ, 2022) as compared to previously modelled farm (564 ha) due to changes in the benchmarking data used in the previous model (Beef+Lamb NZ, 2020a).

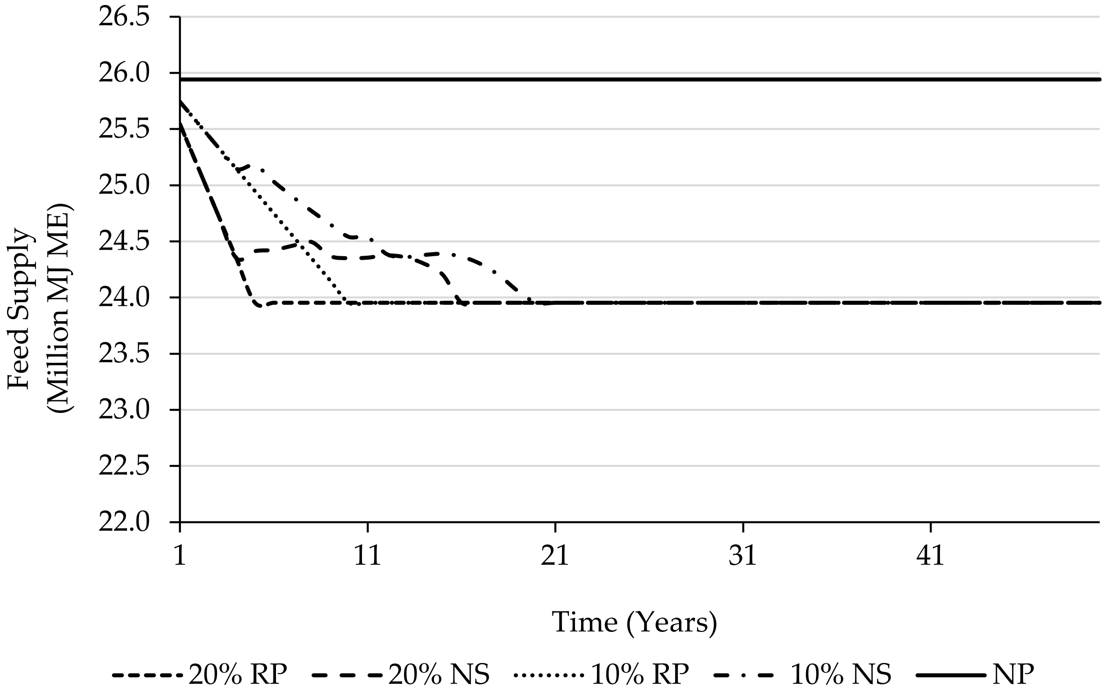

Figure 30. Annual total farm feed supply in megajoules of metabolizable energy (MJ ME) over 50 years for an area equal to 10% of the farm effective area on the steep slope with pasture (NP) or planted in native shrubs (NS) or radiata pine (RP) at two planting rates (10% and 20% per year).

The long-term mean annual farm feed supply on the current farm reduced when 62.4 ha on the steep slope was 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 reduction was 6.5 and 7.0% with native shrubs and by 7.0 and 7.4% with radiata pine at 10 and 20% planting rates, respectively. However, the farm feed supply proportion (6.5 to 7.4%) reduced was less than the proportion of the effective farm area (10%) withdrawn from pastures. This indicates that conversion of pastures to afforestation on the steep slopes has lesser impact on the farm carrying capacity.

7.3.2. 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 30). When 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 hill country sheep and beef farms (Praat, 2011; Lambert, 2014; Kemp, 2016). Conversion of 62.4 ha on the steep slope from pastures to either native shrubs or radiata pine resulted in a decrease in the slope feed supply. The reduction was more with radiata pine (21.2 and 20.0 %) than with native shrubs (20.1 and 18.8%), and greater at the 20% than 10% planting rate, respectively.

Feed supply reduction was more with radiata pine because the afforested area was not used for browsing or understory grazing, unlike with native shrubs. The greater reduction at 20% planting rate can be attributed to large areas (12.8 ha) withdrawn from grazing over a shorter period (5 years) compared to the 10% rate where smaller areas (6.4 ha) were withdrawn and spread over a longer period (10 years). Comparably, the mean feed supply for the steep slope was 1.6 and 1.3% more with natives than with radiata pine at 10% and 20% planting rates, respectively. This shows that native shrubs contributed marginally to the farm feed supply, which can be attributed to utilization of the area in native shrubs only in summer season during the browsing period. The reduction in total feed supply lead to proportionate (%) reduction in feed supply allocated to sheep flock.

Table 30. Modelled farm mean farm 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 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	7,331,967	24,247,935	57.2
	Radiata Pine	4,480,928	12,435,039	7,216,767	24,132,734	57.0
20%	Native Shrub	4,480,928	12,435,039	7,209,707	24,125,675	57.0
	Radiata Pine	4,480,928	12,435,039	7,117,362	24,033,330	56.8

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

The browsing period for the area planted in native shrubs was spread over 15 and 10 years at 10 and 20% planting rates, respectively. Cumulatively, feed supply over the browsing period was more for native shrubs at 10% planting rate (5.8 million MJ ME) than at 20% planting rate (4.6 million MJ ME) (Figure 31). This agrees with earlier findings (Chapter 3) and can be attributed to the longer browsing period for the 10% than the 20% planting rate. Although the area planted annually at 10% was half that at 20% planting rate, multiple overlapping portions were available for browsing and understory grazing resulting in cumulatively more feed supply for the 10% planting rate. The higher cumulative feed supply resulted in higher per hectare feed supply at 10% planting rate (61,935 MJ ME) and was nearly twice that at 20% planting rate (32,793 MJ ME). However, the mean annual feed supply over the browsing period was 9.3% more at the 20% planting rate (419,750 MJ ME) than at 10% planting rate (384,000 MJ ME). The higher mean annual feed supply at 20% would be expected because a large portion (12.48 ha) was available for browsing and understory grazing annually and therefore more feed supply over shorter browsing period (10 years).

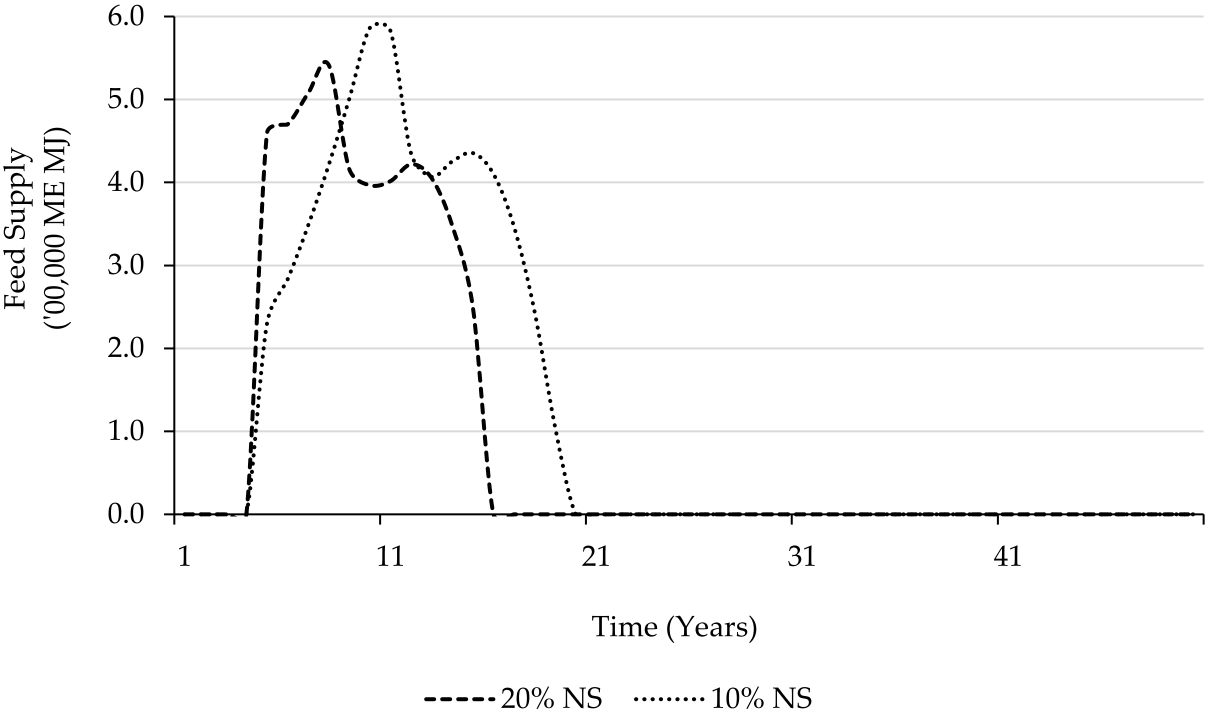

Figure 31. Annual feed supply megajoules of metabolizable energy (MJ ME) over 50 years from the steep slope portion (10% of farm effective area) planted in native shrubs at two planting rates (10% and 20% per year)

7.3.4. 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 (Figure 32). The current modelled farm flock was 11.2% higher than in the previous model (2,747) (Chapter 3) 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, 2022). The difference was because the current model mimicked an individual farm, while (Beef+Lamb NZ, 2022) estimates were based on the mean of 3,055 farms that can vary in farm characteristics, management and flock sizes (Beef+Lamb NZ, 2022). Nonetheless, the ewe flock size (2,413) in the current model was similar to the estimates by (Beef+Lamb NZ, 2022).

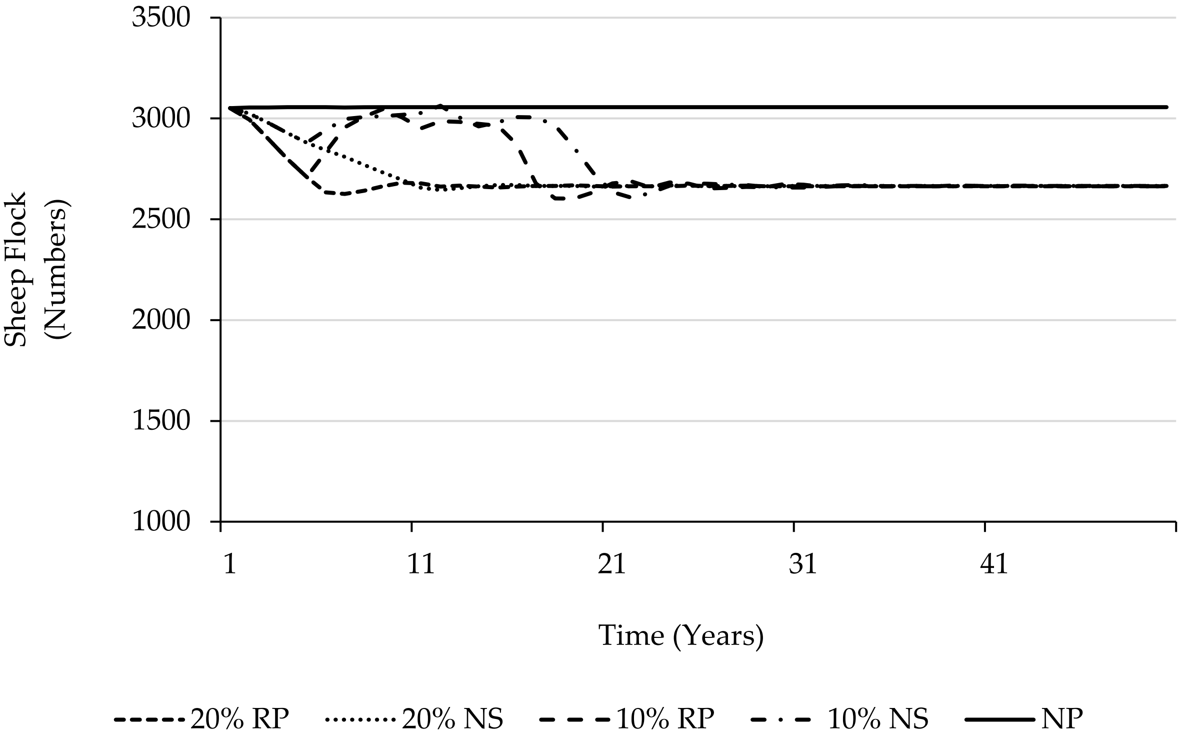

Figure 32. Annual sheep flock size over 50 years for the modelled farm with pastures (NP) or planted in native shrubs (NS) or radiata pine (RP) on an area equal to 10% of the effective farm area on the steep slope at two planting rates (10% and 20%).

As would be expected, the decrease in farm feed supply resulted in the flock size reduction. The overall flock size reduction was more with radiata pine (12.1% and 10.0%) than native shrubs (11.4% and 8.8%) and greater at 20% than 10% planting rate, respectively. The difference in the proportion of flock size reduction between native shrubs and radiata pine occurred because, native shrubs provided some browse and understory feed during the browsing period resulting in a periodic increase in farm carrying capacity. Greater flock reduction at 20% planting rate occurred because of higher reduction in feed supply and due to greater flock adjustments to meet the change in feed supply.

7.3.5. 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 31). Reduction in the farm feed supply during the planting stage of the native shrubs and radiata pine resulted in more lambs sold, which caused a reduction in the 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 flock maintains the flock structure stability (Farrell, 2020b). In addition, adjusting the replacement flock instead of culling mature ewes maintains the ewe flock reproductive performance that peaks at five years (Farrell, 2019, 2020b).

Table 31. Sheep flock size change 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 on the steep slope at two planting rates (10% and 20%).

Flock Structure	Flock size	Native shrubs		Radiata pine	
		10%	20%	10%	20%
Sheep flock	3,055	-8.8	-11.4	-10.0	-12.1
Ewe flock	2,413	-10.6	-11.4	-11.3	-12.0
Replacement flock	605	-2.8	-3.0	-3.0	-3.2

7.3.6. Modelled farm cash operating surplus and farm economics.

The capital for investing in afforestation interventions was internally sourced from the farm proceeds. Net cashflow expressed as cash operating surplus (COS) and the farm economics focused on sheep enterprise because afforestation intervention on the farm affected sheep production only. The sheep enterprise COS comprised of, (a) sheep flock and (b) native shrubs or (c) radiata pine net cashflows. Sheep enterprise COS with pastures referred to the base scenario where no afforestation intervention and constituted only the sheep flock net cashflow. Sheep enterprise COS with native shrubs referred to intervention scenario with native shrubs and comprised sheep flock and native shrubs net cashflows. Similarly, sheep enterprise with radiata pine comprised sheep flock and radiata pine net cashflows. The economic analysis compared the net present value (NPV) of the sheep enterprise with pasture and with native shrubs or radiata pine at 10 and 20% planting rates. Three discount rates (5, 7 and 10%) were applied to consider future inflation uncertainties. Break-even analysis was carried out to determine the carbon price per New Zealand Unit (NZ$/NZU) that would be required to equalize COS for sheep enterprise with afforestation interventions to that for sheep enterprise with pasture. A New Zealand Unit is equivalent to one metric tonne of carbon dioxide equivalent.

7.3.7. Sheep flock cashflow

The net cashflow for sheep flock with pasture had a smooth exponential decrease over the simulation period reflecting the discount rate impact on the constant future net cashflow. Changes in steep slope land use from pasture to either native shrub (Figure 33a) or radiata pine (Figure 33b) resulted in fluctuations in feed supply impacting on the flock size, which affected the number of lambs sold and therefore cashflow for the flock. Withdrawal of portions of pastures from grazing during the planting stage for both native shrubs and radiata pine caused a reduction in the flock size to match feed supply to demand. As shown in section 7.2.3, flock reduction was preferentially through increased sale of lambs, which resulted in higher net cashflow than for the flock with pasture. After planting, the area afforested was not available for grazing and therefore lower flock size was supported on the farm. The lower flock size translated to fewer lambs sold resulting in lower flock net cashflow than with pasture. However, there was gradual increase in flock size during the native shrubs browsing period, which led to a transient increase in lambs sold causing the flock net cashflow to approach that with pasture. On average over the simulation period, radiata pine intervention caused greater flock net cashflow reduction (5.1 and 4.3%) than native shrubs (4.6 and 3.7%) and the reduction was more at 20% than 10% planting rate, respectively compared to the flock net cashflow with pasture (NZ$ 23,897). The greater reduction with radiata pine and at 20% planting rate can be associated to feed supply reduction as elaborated in section 7.2.2.

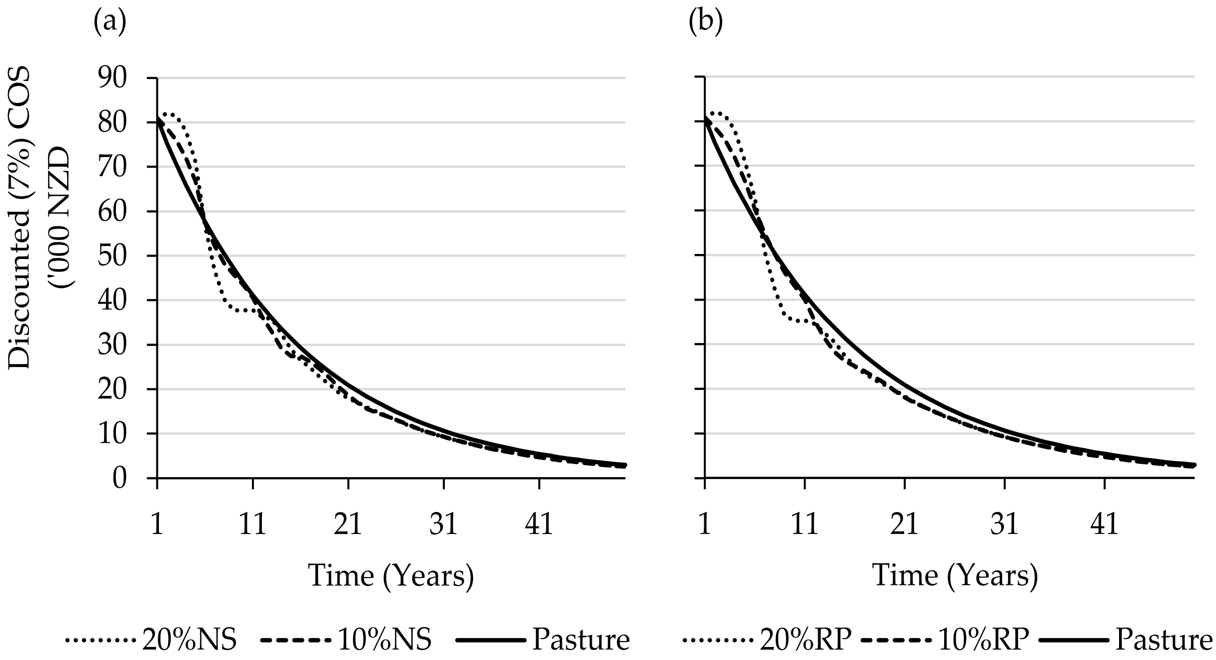

Figure 33. Sheep flock net cashflow at 7% discount rate with pasture and with (a) native shrubs (NS) or (b) radiata pine (RP) planted on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10, and 20%).

7.3.8. Native shrubs and radiata pine cashflow

The discounted total and average annual cashflow over 50 years for radiata pine and native shrubs are shown in Table 32. Average radiata pine cash inflow (carbon trade and logs income) was 112.5% and 117.2% more than the cash outflow at 10 and 20% planting rates, respectively. This indicated that planting radiata pine on the steep slope can be profitable at the current cash inflow and outflow. Post-planting expenses accounted for the largest proportion of the cash outflow at 90.4% and 91.2% while land preparation accounted for 5.4% and 4.9% and planting 4.2% and 3.9% at 10 and 20% planting rates, respectively. The high post-planting expenses for radiata pine was due to tree management and harvesting operations.

Contrastingly, cash outflow (expenses) exceeded cash inflow (carbon trade income) for the native shrubs suggesting that native shrubs intervention was not a profitable intervention at the current carbon price vis a vis the expense. Native shrubs planting (45.8% and 43.5% of the total expenses) and post-planting (47.7% and 47.7% of the total expenses) expenses accounted for the largest proportion of cash outflow at 10% and 20% planting rates, respectively. Native shrubs seedling (NZ$ 2.65/ seedling) accounted for 80.6% of the planting cost. This suggests that reducing native shrubs seedling price could significantly lower the planting expenses and increase net cashflow.

Comparably, native shrubs seedlings price was approximately eight times more than radiata pine seedlings (NZ$ 0.3/ seedling) (Askin, 2018).

The high net cashflow for radiata pine compared to the native shrubs can be attributed to the greater carbon stock accumulation that is approximately three times that of native shrubs (Ministry for Primary Industries, 2017) and the extra income from sale of logs (Maclaren, 1993). Despite the low financial returns, native shrubs have numerous non-financial benefits. Socially, some native shrubs have cultural values and others are used for crafts, ethnomedicine, and as ornamental plants (Brooker, 1989). Ecologically, they provide habitat to wild fauna and act as nursing plants to higher canopy flora (MacGibbon, 2014). Because of their diversity in growth forms and adaptation to different ecological niche, they complement in landscape restoration and aesthetics (Dodd, 2007). In addition, some native shrubs are preferred and browsed by wild herbivores (Williams, 1982; Forsyth, 2002, 2005; Bee, 2011) and therefore would be expected to be a source of forage to the farmed ruminants. Results from chapter 4 and 5 have shown that native shrubs can be superior to summer pastures in metabolizable energy but are generally lower in crude protein. Environmentally, native shrubs provide continuous ground cover and soil reinforcement for longer periods than commodity trees that have determined harvest cycles (Hawke’s Bay Regional Council, 2004).

These non-monetary benefits for native shrubs and cost associated with erosion control and environmental restoration after harvesting the radiata pine trees were not included in the model. The native shrubs benefits and post-harvest costs associated with radiata pine plantations can significantly impact on the net cashflow for native shrubs and radiata pine when utilized on the steep slope (Satchell, 2018).

Table 32. Cashflow (total and annual average) 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 at 20 and 10% planting rates.

Cashflow	Planting rate (%)	Native shrubs			Radiata pine			
		Carbon Income	Total Expenses	Net Cashflow	Carbon Income	Logs Income	Total Expenses	Net Cashflow
Total	20	193,895	224,429	-30,534	554,597	770,662	610,043	715,216
	10	226,383	271,946	-45,563	647,520	915,139	735,242	827,417
Annual average	20	3,878	4,489	-611	11,092	15,413	12,201	14,304
	10	4,528	5,439	-911	12,950	18,303	14,705	16,548

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

The sheep enterprise COS trend over the simulation period with native shrubs planted on the steep slope is shown on Figure 34. Compared to sheep enterprise COS with pastures, COS with native shrubs at both 10 and 20% planting rates was lower except during carbon cash inflow years (sharp peaks). The lower COS with native shrubs can be attributed to establishment expenses that were drawn from the sheep flock COS. The land preparation and planting expenses (first five years) were higher at 20% planting rate resulting in lower COS than with 10% rate and with pasture. The first carbon cash inflow at both 20% than 10% planting rate was low to offset the cash outflow which made COS with native shrubs lower than with pasture. Carbon cash inflow for the second to fourth instalment exceeded the cash outflow and made COS with native shrubs at both 10 and 20% more than with pastures. However, COS with native shrubs at 10% in the fifth and sixth carbon cash inflow exceeded that at 20% planting rate and with pasture because there were multiple portions of land planted in native shrubs that were still within the carbon trading period. On average, annual COS with native shrubs was 6.3% and 8.4% lower than with pasture (NZ$ 23,897) at 10% and 20% planting rate, respectively. The marginally higher reduction in COS with native shrubs planted at 20% annual rates can be attributed to lower feed supply supporting a lower flock size and therefore fewer lambs sold compared to native shrubs planted at 10% rate.

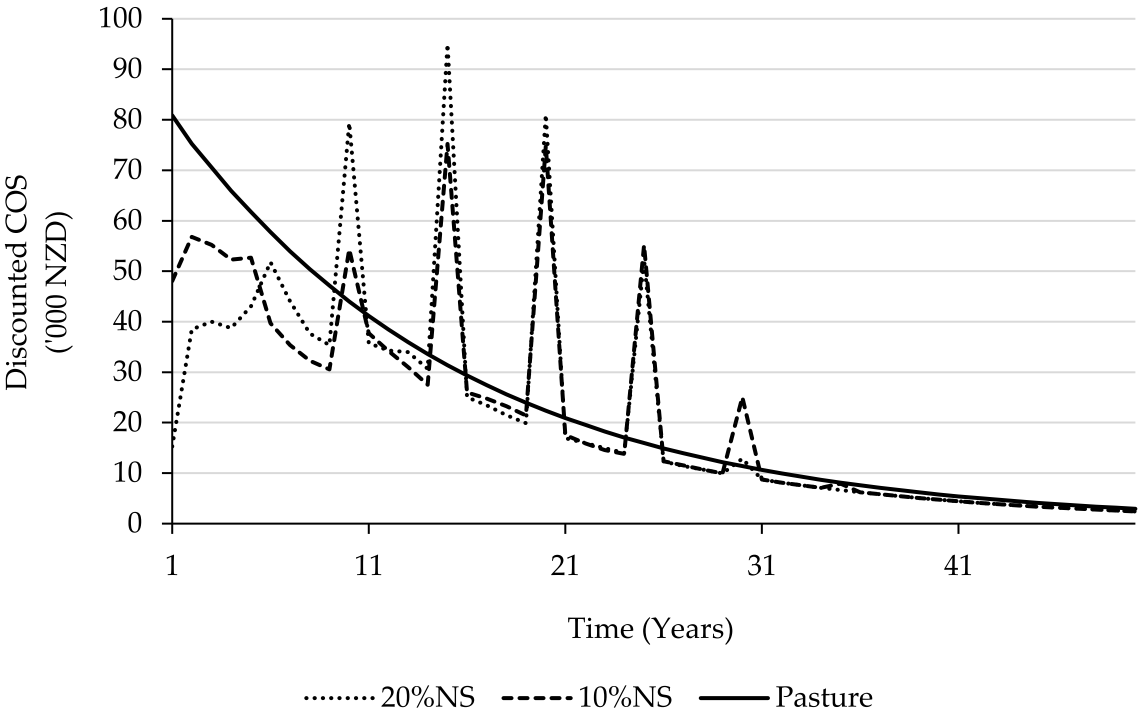

Figure 34.Sheep enterprise cash operating surplus (COS) at 7% discount rate with pasture and with native shrubs planted on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10, and 20%).

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

The sheep enterprise COS with radiata pine was lower than with pasture along the simulation period except during carbon and log cash inflow years (Figure 35). Similar to the native shrubs, the lower COS with radiata pine can be attributed to the establishment expenses that were drawn from the sheep flock COS. Land preparation and planting expenses (first five years) were higher at 20% planting rate resulting in lower COS than at 10% rate and with pasture. The COS with radiata pine at 20% was more than with 10% planting rate and with pastures in the first two carbon cash inflows but was lower than with 10% planting rate for the other carbon cash inflow. In addition, COS with radiata pine at 20% was more than at 10% planting rate and with pasture during log cash inflow but took half the time of that for the10% rate, after which it was lower than at 10% rate and with pasture. On average, the sheep enterprise with radiata pine was 64.2% and 55.6% more at 20% and 10% planting rate, respectively than with pasture (NZ$ 23,897). The greater COS with radiata pine than with pasture can be associated with the higher carbon cash inflow and extra cash inflow from logs that resulted in surplus COS after offsetting establishment expenses.

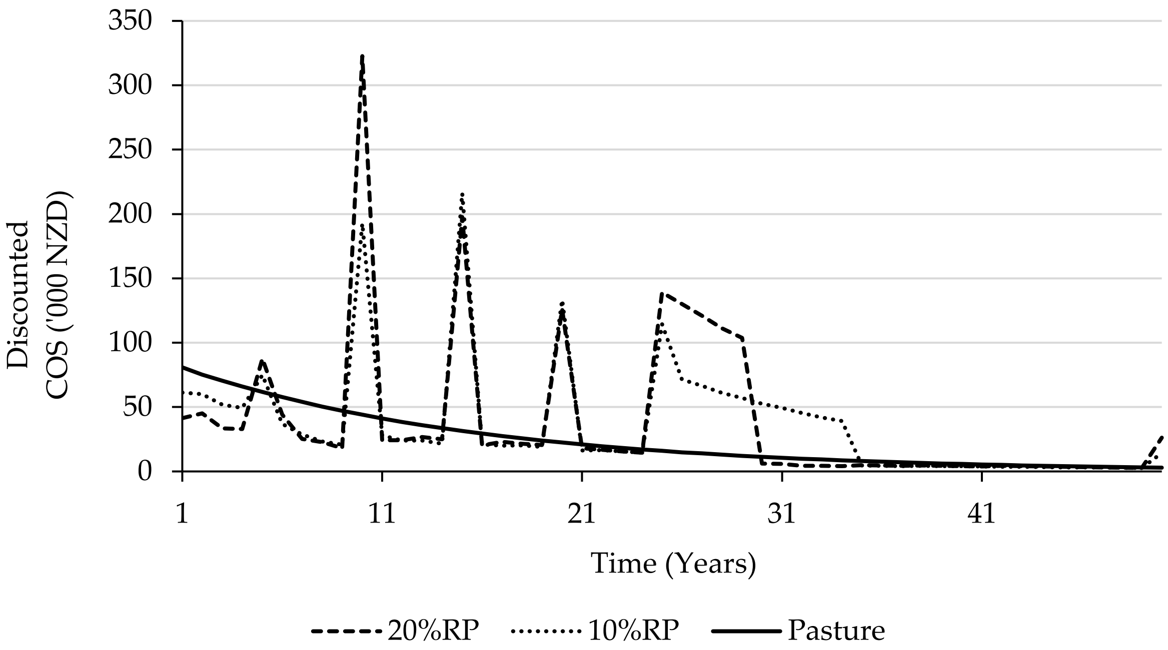

Figure 35. Sheep enterprise cash operating surplus (COS) at 7% discount rate with pasture and with radiata pine planted on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10, and 20%).

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

Table 33 shows the net present value (NPV) at three discount rates (5, 7 and 10%) for the sheep enterprise with pastures and with native shrubs or radiata pine planted at 10% and 20% planting rates on the steep slopes. The NPV for sheep enterprise with native shrubs at both 10% and 20% planting rates was lower than with pastures at all the discount rates. This would be expected because native shrubs intervention had an overall negative net cashflow resulting in use of sheep flock proceeds to offset the deficit. As expected, the NPV with native shrubs reduced with increase in discount and planting rates. Reduction in NPV with higher discount rate can be expected because future net cashflow reduces in value as discount rate increases (The Treasury, 2008). Planting large area annually (20% planting rate) with native shrubs led to higher negative net cashflow resulting in lower NPV. This suggests that at the current native shrubs net cashflow, planting native shrubs at higher annual rates will lead to greater reduction in sheep enterprise proceeds. A similar observation was made for sheep enterprise with native shrubs with carbon price at 32 NZ$/NZU (Chapter 3).

The NPV for the sheep enterprise with radiata pine at either planting was higher than with pastures for the three discount rates, unlike with native shrubs. This occurred because overall COS for sheep enterprise with radiata pine exceeded that with pasture. Like with native shrubs, the NPV with radiata pine reduced as discount rate increased. Unlike with native shrubs, NPV with radiata pine was higher at 20% than 10% planting rate for the three discount rates. The low NPV with radiata pine at 10% planting rate was because the cash inflows (carbon and logs) were spread over double the number of years that of radiata pine at 20% planting rate. Consequently, the cash inflows on the latter half of spread period for radiata pine at 10% planting had a greater reduction in value due to the impacts of discounting explaining the lower NPV. This implies that radiata pine would be more profitable when planted at higher planting rates at the three discount rates.

Table 33. 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 on the steep slopes at three planting rates (10 and 20%)

Discount Rate	Pastures	Native Shrubs		Radiata Pine	
		10%	20%	10%	20%
5%	1,659,762	1,565,263	1,506,417	2,702,466	2,784,018
7%	1,278,418	1,168,928	1,108,490	1,909,762	1,979,532
10%	943,999	820,827	755,139	1,236,942	1,277,445

7.3.12. Break-even carbon price for sheep enterprise with native shrubs

The modelled carbon price (63.53 NZ$/NZU) resulted in higher NPV for the sheep enterprise with radiata pine and lower with native shrubs than with pasture. Therefore, estimation of the break-even carbon price was only carried out for the sheep enterprise with native shrubs (Table 34). The estimated break-even carbon price was higher at all discount and planting rates than estimated in Chapter 3. This occurred because the current model used a generalized native shrubs allometric function to estimate native shrub growth and therefore carbon stock accumulation (Chapter 6), while the previous model modulated native shrub growth using *Eucalyptus saligna* (Eucalyptus) growth rates, thus affecting estimated carbon stock accumulation (Chapter 3). Although carbon stock accumulation per unit area is finite (Ministry for Primary Industries, 2017), carbon stock accumulation in plants depends on the species (Chapter 6) and density (Bergin, 2014b; Easdale, 2018). Eucalyptus has a fast growth rate and therefore faster carbon accumulation (McKenzie, 1996) compared to native shrubs which have a relatively lower growth rate (Chapter 6). As a result, carbon accumulation for native shrubs in Chapter 3 peaked after 16 years while in the current model they peak after 23 years. Because of the deferred carbon accumulation in the current model, discounting led to lower carbon cash inflow. In addition, the current model used the averaging carbon-accounting method while the previous model (Chapter 3) was based on the stock-change carbon-accounting method. The averaging accounting method limits carbon trade after the native shrubs attain an average age of 23 years (Kiro, 2022), while the stock-change method allowed for carbon trade over the whole simulation period (50 years) (Chapter 3), this led to lower carbon income for the current model. Combined, the greater discounting impact on deferred carbon income and lower carbon income with averaging-accounting method led to a greater reduction in the native shrub net cashflow resulting in a higher break-even carbon price. However, the relative change between the modelled carbon price and the estimated break-even price was lower for the current model compared to the previous model (Chapter 3).

Table 34. Break even carbon price per New Zealand Unit (NZ$/NZU) at three discount rates (5, 7 and 10%) of using native shrubs on an area equal to 10% of the effective farm area on the steep slopes at two planting rates (10 and 20%)

Planting rate (%)	Discount rate (%)		
	5	7	10
10	85.0	99.4	130.9
20	94.6	111.3	147.2

The break-even carbon price relative to the modelled price (63.53 NZ$/NZU) rose with increase in planting and discount rate. This can be attributed to greater negative net cashflow at 20% planting rate, which was elevated with increase in discount rate. The negative net cashflow for native shrubs resulted because establishment expenses exceeded the carbon income (section 7.3.8). Therefore, this suggests that reduction of establishment expenses and increasing carbon income can make the native shrubs profitable. Some direct approaches that can reduce native shrubs establishment expenses include, reduction in seedling prices, provision of native shrubs establishment grants and allowing for natural revegetation. Strategies that can increase carbon income include, prime price for native shrubs carbon and increasing carbon trade typical average years for native shrubs. Other strategies can include diversity credits and integration of other activities such as honey production. Allowing for longer browsing periods can also support more sheep, thereby increasing income from the sale of lamb.

7.4. Conclusion

The inclusion of radiata pine sub-model to hill country sheep and beef farm model allowed for comparison of the impacts of planting either native shrubs or radiata pine on 10% of the farm effective area on the steep slopes on farming system. Planting of either native shrubs or radiata pine led to a decrease in farm feed supply and this effect was greater at 20% planting rate and with radiata pine. The proportional decrease in farm feed supply was lower than the proportion of the farm effective area withdrawn from pastures, indicating that afforesting the steep slopes would have lesser effect on the 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. Radiata pine had net cashflow in surplus because of higher carbon and log incomes and exceeded the reduced sheep flock net cashflow resulting in higher sheep enterprise cash operating surplus than the base scenario. Conversely, native shrubs had a negative net cashflow due to low carbon income and high seedling costs and combined with the reduced sheep flock net cashflow led to a lower sheep enterprise cash operating surplus compared to the base scenario. This suggests that at the current prices and based on monetary value, radiata pine would be more attractive to farmers. The carbon price required to make planting native shrubs break-even to the base scenario was 85.0 NZ$/NZU and 147.2 NZ$/NZU for the best- and worst-case scenarios, respectively tested in this study. This suggests that policy interventions aimed at lowering the cost of seedlings and making carbon income comparable to that of radiata pine can make planting native shrubs profitable and an attractive investment on hill country farms. However, this study did not consider other monetary and non-monetary benefits of native shrubs and radiata pine post harvesting expenses, which can affect their net cashflows.

Chapter 8: General Discussion and Conclusion

8.1. Introduction

This thesis of work aimed to fill the information gaps on the potential use of browsable native shrubs on the steep slopes of New Zealand hill country sheep and beef farms. The aim was addressed using five specific objectives structured into five research chapters as follows.

1. Assessment of the impact on farm feed supply, flock size, and economics of planting native shrubs on the steep slope (10% of farm effective area) of a modelled hill country sheep and beef farm (Chapter 3),
2. Evaluation of the nutritional composition of browsable native shrubs (Chapter 4),
3. Determination of the *in vitro* fermentation kinetics, fermentation products (volatile fatty acids, microbial protein, and greenhouse gases) and digestibility of browsable native shrubs (Chapter 5),
4. Estimation of the components (stem, branch, and foliage) and aboveground biomass and developing allometric functions predicting biomass variables and carbon stock of native shrub (Chapter 6), and
5. Comparison the impact on farm feed supply, flock size and economics of planting either native shrubs or radiata pine on the steep slope (10% of farm effective area) of a modelled hill country sheep and beef farm (Chapter 7).

This general discussion has been organised by research theme: nutritional value of browsable native shrubs (Chapters 4 and 5); native shrub biomass and carbon stock (Chapter 6); and bioeconomic modelling (Chapters 3 and 7). The summary of main findings, limitations, suggested future research and implications are outlined in the following sections.

8.2. Summary of the main findings

8.2.1. Nutritional value of browsable native shrubs (Chapter 4 and 5)

The nutritional composition of five native shrubs (*C. robusta*, *G. littoralis, H. populnea*, *P. crassifolium* and *P. arboreus*) was evaluated across three seasons (summer, winter, and spring) and compared to an exotic osier willow (*S. schwerinii*) in Chapter 4. *In vitro* fermentation characteristics for the shrub species was determined during the spring season except for *P. arboreus* due to insufficient sample quantity. The native shrubs used are amongst the most common in New Zealand and have been shown to have potential as browsable species (Lambert, 1989a; Forsyth, 2002, 2005).

The results from this thesis showed that nutritional composition, for all the shrubs, was affected by season but the variation was greater for *S. schwerinii* than the native shrubs. Native shrubs showed diversity in nutritional composition but were generally superior in metabolizable energy (ME) and lower in crude protein (CP) than *S. schwerinii*. Overall, the data suggested that native shrubs can be used to supplement the low ME in pastures during summer. However, the CP for the native shrubs was generally not variable across the seasons and was below the minimum requirements for ruminants if used as a sole feed source (Waghorn, 2004; Yang, 2018; Hynd, 2019).

The *in vitro* fermentation characteristics were distinct between native shrubs and *S. schwerinii*. Native shrubs yielded higher total volatile fatty acids (VFA) and greenhouse gases indicating they were more digestible than *S. schwerinii*. Conversely, *S. schwerinii* had more microbial biomass (MBM) indicating lower rate of microbial turnover than native shrubs. This shows that when consumed by farmed ruminants, native shrubs would be of greater nutritive value due to high VFA, MBM turnover, and digestibility but would produce more greenhouse gas emissions than *S. schwerinii*.

8.2.2. Estimated native shrubs biomass and carbon stock (Chapter 6)

Three native shrubs species (*C. robusta, M. ramiflorus* and *P. crassifolium*) were sampled from two sites and used to estimate shrub components (foliage, branch, and stem) and aboveground biomass. The biomass data was used to estimate carbon stock and to develop allometric functions predicting both biomass variables and carbon stock for the shrubs.

Results for biomass estimation showed that species and site did not affect aboveground biomass accumulation for the native shrubs. However, the shrubs showed differences in biomass partitioning to the various components that affected their estimated total carbon stock. Generally, the shrubs had indistinct stem biomass and *M. ramiflorus* had lower foliage biomass and *C. robusta* lower branch biomass. *Pittosporum crassifolium* contained greater total carbon stock because of higher woody biomass accumulation but this was lower than is estimated for exotic species (Ministry for Primary Industries, 2017). The results showed that native shrubs can be diverse in biomass partitioning to the components and in carbon stock accumulation. A generalized allometric function using basal diameter was sufficient to predict aboveground biomass for the native shrubs. Equally, a generalised allometric function using the shrub volume was sufficient to predict native shrubs' foliage biomass. However, species specific allometric function would be needed to estimate stem biomass mainly because of differences in native shrub growth habits.

8.2.3. Impacts on farm feed supply, flock size and farm economics of using either native shrubs or radiata pine on hill country sheep and beef farms (Chapter 3 and 7).

Bioeconomic models used in Chapter 3 and 7 had similar structure except for the radiata pine module that was added in Chapter 7. In addition, the two models (Chapter 3 and 7) used different farm effective area and flock size due to industry changes over the period of study (Beef+Lamb NZ, 2020a, 2022). Further, the native shrubs modules in the two Chapters used different data sources to model native shrub growth and fodder quality and methods for carbon accounting. The model in Chapter 3 used the stock change (sawtooth) carbon accounting method (Ministry for Primary Industries, 2017) with annual allocation of carbon credits. Conversely, the model in Chapter 7 used the averaging carbon accounting method with allocation of carbon credits every five years until the typical average age was attained where no more carbon was allocated for trading (Kiro, 2022). The differences in carbon accounting methods was because the native shrubs in Chapter 3 were assumed to be planted in the year 2020 when stock change method was in effect, while native shrubs or radiata pine in Chapter 7 were planted post 2023 when the averaging method was the compulsory technique (Kiro, 2022).

The results from the two models (Chapter 3 and 7) showed that planting native shrubs or radiata pine, respectively, on the steep sloped land led to a reduction in farm feed supply. The reduction was greater at higher planting rate of the native shrubs and with radiata pine due to no understory pasture. The reduction in farm feed supply caused a decline in the farm sheep flock. Overall, the flock size reduction was marginally lower with native shrubs because of the extra feed supply during the browsing period. The reduction in flock size with planting of native shrubs or radiata pine caused a decrease in lambs sold and therefore the sheep flock net cashflow. In both Chapter 3 and 7, the net cashflow for native shrubs was negative, which when combined with the decreased sheep flock net cashflow made the sheep enterprise unprofitable. The negative net cashflow for native shrubs was attributed to low carbon income and high seedling cost. The estimated break-even carbon price that would equalize net cashflow for the sheep enterprise with native shrub to that with pasture was lower in Chapter 3 than 7. This occurred because native shrub growth in Chapter 3 was modeled using *Eucalyptus saligna* as it was the only data available. Eucalyptus has a fast early growth rate that led to more carbon cash inflow in early years that was minimally reduced by discounting. In addition, the use of the stock-change carbon-accounting method in Chapter 3 resulted in higher carbon cash inflow. In contrast, the net cashflow from radiata pine (Chapter 7) was positive and exceeded the reduced net cash flow for the sheep flock making the sheep enterprise more profitable. Therefore, based on monetary value only and current prices, radiata pine would be a more desirable option for farmers. However, native vegetation has numerous monetary and non-monetary benefits (Dodd, 2007; Bergin, 2014b) while radiata pine can attract other extra expenses such as environmental restoration after harvesting (Maclaren, 1993; Satchell, 2018), which can impact on net cashflow but were not included in this study.

8.3. Limitations of the study

8.3.1. Nutritional composition and in vitro fermentation of browsable native shrubs (Chapter 4 and 5)

Native shrubs foliage samples for nutritional composition (Chapter 4) and *in vitro* fermentation (Chapter 5) studies were obtained from five species planted on a trial site at Manawatu Massey University Dairy 4 farm. Nutritional composition of forages can vary between geographical location due to differences in environmental conditions and soil properties (Ledgard, 1982; Chapman, 1985). Foliage samples used in Chapter 4 and 5 were sourced from a single site and therefore inferences cannot be generalized to represent the different environmental conditions and soil properties found across New Zealand.

There are numerous native shrubs that are consumed by wild herbivores in New Zealand (Mitchell, 1987; Lambert, 1989a; Forsyth, 2002, 2005) that can be potential source of fodder for farmed ruminants. However, because of limitation of the space on the trial site (planted before this PhD program started) only a few that are included in this study were investigated. The native shrub foliage in this study was assumed to be consumed by sheep although it is known that preference and intake of forages can vary among the different herbivore classes (Mitchell, 1987; Lambert, 1989a; Forsyth, 2002, 2005). It has been recently shown that sheep do consume all the native shrubs utilized in this study if offered to them (unpublished data). However, sheep browsing preference and intake of the native shrubs *in situ* remains unknown.

Nutritional composition in plants can vary with age as leaves and edible stems mature and lignify (González-Zurdo, 2016). The native shrubs used in this study were juvenile (approximately 3 years) and therefore did not include foliage from mature plants. In addition, the native shrubs had low foliage production especially in winter and summer seasons resulting in low foliage sample quantities. The low foliage sample quantities were insufficient to carry out both nutritional composition assay and *in vitro* fermentation for the two seasons (winter and summer) and hence the nutritional composition assay was prioritized. As a result, the *in vitro* fermentation characteristics across seasons for the native shrubs was not investigated. Studies on willows and poplars in New Zealand have shown sheep can eat edible stems of up to 5 mm in diameter (Oppong, 2001; Kemp, 2003) and this was assumed for the native shrubs foliage. Anecdotally, native shrubs had smaller edible stem diameter (<5 mm) disproving the assumption of likely similar edible stems diameter to exotic species.

8.3.2. Native shrubs biomass and carbon stock (Chapter 6)

Three native shrubs species dominant in Limestone Down and at the Manawatu Massey University nature reserves were destructively sampled to estimate the biomass and carbon stock of native shrubs and to develop the predictive allometric functions. The sampled shrubs had basal diameter of less than 10 cm despite some native shrubs such as *M. ramiflorus* reported to grow to basal diameters of above 30 cm (Poole, 1994; Metcalf, 2011). Although the two sites represented two contrasting geographical locations and environmental conditions in the North Island, they were not representative of all climatic conditions, topography, and soil types across New Zealand. Further, the three species used in the study represented a small proportion of the over 400 endemic native shrubs species in New Zealand (Merrett, 2006; Kerr, 2014), which can vary in biomass and carbon stock characteristics.

Native shrubs in nature reserves are commonly in high density (>5,000 sph) as compared to the recommended planting density of <5,000 sph aimed to reduce cost of establishment (Bergin, 2014b). Although biomass, and, therefore, carbon stock accumulation is finite per unit area, individual plant biomass is influenced by stocking density of plants (Poorter, 2012b). Therefore, individual native shrubs planted at lower densities on the farm can be expected to have higher biomass and carbon stock accumulation than those used in this study, although this is not known.

8.3.3. Bioeconomic modelling (Chapter 3 and 7)

A bioeconomic model with native shrubs sub-model (NSM) added to hill country sheep and beef farms model (HCM) (Farrell, 2020) was used in Chapter 3. The NSM sub-model in Chapter 3 was based on limited native shrub literature data but the gaps were compensated using existing exotic species trees, shrubs, and pasture data. Some of the data gaps regarding native shrubs were addressed in Chapters 4, 5 and 6 and used to update the NSM sub-model. The HCM model used in Chapter 7 had a radiata pine sub-model in addition to the updated NSM sub-model. Limitations for HCM are detailed previously by (Farrell, 2020) and those for NSM sub-model used in Chapter 3 are described in Chapter 7. Therefore, only limitations for radiata pine sub-model (RPM) and the updated NSM sub-models in Chapter 7 are outlined.

Hill country farms can vary in the area of flat, rolling and steep slopes classes and respective pasture productivity across New Zealand (Lynn, 2009; Praat, 2011; Trafford, 2011; Lambert, 2014; Kemp, 2016). The effective farm area partitioning into the slope classes (Beef+Lamb NZ, 2022) and their respective pasture productivity in this study was based on an average hill country farm on the East Coast region of New Zealand (Trafford, 2011), and, therefore cannot be generalized for other hill country areas in New Zealand. However, the model has the capabilities to simulate other farming systems.

The growth, foliage biomass and carbon stock of native shrubs were estimated using generalized allometric functions based on native shrubs data from Limestone Downs and Manawatu Massey University nature reserves (Chapter 6). The allometric functions were estimated using only a few native shrubs species and a relatively small sample size. This can be improved with inclusion of more species and samples across the basal diameter range and ecoclimatic zones in New Zealand. The generalized allometric functions were assumed to be representative of the modelled farm site (East Coast region), but it is known that the dominant native shrubs species can vary across geographical locations (Poole, 1994; Metcalf, 2011) and therefore can affect the biomass and carbon stock allometric functions. In addition, individual plant biomass, and, therefore, carbon stock can be affected by plant density (Poorter, 2012b). The allometric functions used in the study were derived using samples from native shrubs growing in nature reserves under high density (approximately 8,500 sph). Although a correction factor was used to adjust biomass and carbon stock to that expected when shrubs are planted on the farm at 2,000 sph, the adjustments can only be ascertained using nelder spacing data that is lacking for native shrubs.

Native shrubs can have numerous monetary and non-monetary benefits (Dodd, 2007; Bergin, 2014b), which can affect net cashflow but only carbon cashflow was used in the study. In addition, proposed benefits such as grants, biodiversity credits and premium carbon prices which can increase net cashflow for native shrubs (Clough, 2000; Department of Conservation, 2014; PwC New Zealand, 2020; Kaine et al., 2022) were not considered. Conversely, harvested radiata pine areas are prone to erosion and storm-washed slash can cause damage to properties, infrastructure, and the environment (NZ Farm Forestry, 2007; Satchell, 2018) resulting to additional expenses that can lower net cashflow. The potential expenses that can arise post radiata pine harvesting were not considered in the model.

8.4. Future Research

8.4.1. Nutritional value of browsable native shrubs

The results has revealed that native shrubs have superior ME to *S. schwerinii* across the seasons and can be a potential source of supplementary fodder during summer when pastures are low in ME. However, this is based on assumption that sheep will prefer and consume the native shrubs. A preliminary study using the native shrubs in this study showed that housed sheep can consume native shrubs if offered to them (unpublished data). This was in agreement with an earlier study using a set of different native shrubs and two grasses (Lambert, 1989a). However, there's need to examine sheep preference and intake of the native shrubs *in situ* to verify the assumption and guarantee their suitability as potential fodder sources when planted on the farm. In addition, *in situ* trials will provide information on sheep browsing behavior, browse height and native shrubs response to defoliation which is important in planning browse use and management in the farm.

Nutritional composition and *in vitro* fermentation characteristics in this study were from juvenile shrubs and therefore studies including mature shrubs would be required to characterize any change in nutritive value as they age. The *in vitro* fermentation characteristics of the native shrubs were only conducted for the spring season indicating the need for studies for summer and winter seasons. This would be necessary because nutritive quality of foliage is affected by seasonal changes which in turn affects digestibility and rumen fermentation properties and products. In addition, *in vivo* feeding studies would be required to compare and calibrate the *in vitro* fermentation and digestibility findings. Further, studies are required to determine whether native shrubs contain non-nutritive compounds that are beneficial or detrimental to the sheep that will guide on their use as feed resources on the farm.

Nutritional composition of plants can vary across geographical regions because of differences in environmental conditions and soil properties (Trafford, 2011). In addition, the study has shown that native shrubs are diverse in their nutritional composition. Because only a single site and few native shrubs species were used in this study, including other sites would enable profiling and comparison of nutritional value of various native shrub species from across the New Zealand ecoclimatic zones. Determining their nutritional value can add to the information gap on native shrubs and widen the fodder source options for farmers.

8.4.2. Native shrubs biomass and carbon stock

Results from this study showed that native shrub species can be diverse in biomass partitioning to the components (branch, foliage, and stem) and in carbon stock. Only two sites were used in the current study yet it’s known that biomass accumulation and therefore carbon stock can vary across locations (Poorter, 2012b). Studies including more native shrubs would enable categorization of the native shrubs on their biomass and carbon stock properties. In addition, inclusion of native shrubs from more sites and age across New Zealand will enable development of robust location specific and generalized allometric functions for biomass and carbon stock estimation. This is essential in carbon stock estimation for emission trading scheme which is currently generalized for native shrubs (Ministry for Primary Industries, 2017). A potential gap in native shrubs knowledge is the lack of nelder spacing studies that can support development of biomass allometric functions specific to densities for planted native shrubs on the farm.

8.4.3. Bioeconomic model used in the study.

The NSM sub-model considered only carbon income as the major cash inflow from native shrubs. However, it is known that native shrubs can have other monetary and non-monetary benefits. In addition, there are incentives such as grants and proposed market benefits such as biodiversity credits and premium carbon price aimed at encouraging farmers to plant native shrubs. These incentives and proposed market benefits can increase the native shrubs net cashflow making them more profitable than in the current study. It is also known that harvesting radiata pine makes the land prone to erosion and storm-washed slash can cause damage to properties, infrastructure, and the environment resulting in extra expenses which can reduce the net cash flow from the enterprise. Inclusion of these cashflows for the native shrubs and radiata pine not used in this study can therefore improve their monetary comparison. Further, a module to estimate the greenhouse emissions can be included in the model to compare the carbon footprint of using pasture vis a vis afforestation species. Including the greenhouse gases footprint can improve decision making on the most suitable intervention with minimal environmental impact on hill country farms.

8.5. Implications of the study

8.5.1. Implication for farmers and policy

Hill country sheep and beef farms typically contain a significant amount of native vegetation mainly on the remote and unusable areas indicating they are already well positioned to develop their biodiversity conservation (Beef+Lamb NZ, 2018b). The farms’ steep slopes are highly vulnerable to soil mass movement (StatsNZ, 2019a) and are predominantly utilized for grazing sheep at low stocking density (Morris, 2013; Beef+Lamb NZ, 2020b). Planting browsable native shrubs on portions of the steep slopes would support native vegetation conservation (Beef+Lamb NZ, 2018b) and stabilize the soil (Phillips, 2005), but their use as browse for sheep has not been investigated previously. Chapter 4 and 5 results revealed that native shrubs were superior in nutritional value to the osier willow that is often used on hill country farms as supplementary fodder during the summer season, when pastures are of low quality. Farmers could successfully substitute willows with native shrubs to provide supplementary browse of good nutritional quality during the summer (Litherland, 2017). Whilst Chapter 5 showed that rumen fermentation of native shrubs yields higher greenhouse gas production compared to the willow, Chapters 3 and 7 revealed that the quantity of native shrubs browsed by sheep would likely account to less than 1% of the total feed supply. This suggests a minor contribution of the browse to greenhouse gas footprint of the farm. In addition, conversion of pasture to native shrubs on the steep slope portions could significantly lower emissions associated with pasture management and increase carbon dioxide sequestration (Kimberley, 2014, 2021).

It is well known that biomass accumulation and partitioning to different plant components is species specific (Poorter, 2012a, 2015). Chapter 6 revealed that native shrubs are diverse in accumulation of aboveground biomass and partitioning of biomass to the various components. The results demonstrated that the choice of native shrub species planted on the farm would influence the foliage biomass available for browsing and the total accumulated carbon stock. This suggests that farmers would be better off planting mixed native shrubs because they would complement each other regarding foliage and carbon stock accumulation. Planting mixed native shrubs would also enhance the farmed landscape aesthetics and biodiversity. The generalized estimation of native shrub carbon stock for the emission trading scheme in New Zealand is well established (Ministry for Primary Industries, 2017; Kimberley, 2021). However, Chapter 6 shows that native shrubs differ in carbon stock, with some exceeding the generalized estimates (Kimberley, 2021). This indicates the need to group native shrubs based on their carbon stock accumulation and estimating carbon stock for the emission trading scheme based on the dominant species on the farm.

The sheep flock accounts for the largest net cashflow in hill country sheep and beef farms (Beef+lamb NZ, 2021). Chapter 7 showed that planting native shrubs or radiata pine on the steep slope would cause a reduction in the flock size and therefore a reduction in the net cashflow from the sheep flock. Net cashflow from native shrubs was negative and therefore their inclusion in the farm would be unprofitable, unlike radiata pine that had surplus net cashflow. The negative net cashflow associated with planting native shrubs was largely due to high seedling costs (Dodd, 2007; Bergin, 2014b) and low carbon trade income (Kimberley, 2021). Therefore, planting native shrubs on these farms would depend on the farmers financial situation and their interest in biodiversity conservation and profits. However, it is possible to lower native shrubs seedling costs and increase carbon income through interventions such as optimized methods of seedling production, prime carbon price for native plants, biodiversity credits and grants (Clough, 2000; PwC New Zealand, 2020; Te Uru Rākau, 2020), but these interventions were not examined in this study.

8.6. General Conclusion

The objective of this thesis was to help fill knowledge gaps on the potential use of browsable native shrubs on steep slopes of hill country farms, through a series of studies and via bioeconomic simulation modeling. The results for nutritional composition suggest native shrubs are superior to *S. schwerinii*. *In vitro* fermentation characteristics indicated that native shrubs were highly digestible, had higher volatile fatty acids, microbial proteins, and greenhouse gases than *S. schwerinii*. Biomass results showed that native shrubs had similar aboveground biomass accumulation but varied in allocation to various components (foliage, branch, and stem). Therefore, the results of these studies showed that native shrubs have the potential to serve as a source of browse feed and carbon accumulation in the farm. Based on the bioeconomic model simulation using data from these studies, it was found that planting native shrubs on steep slopes is not currently a profitable investment based on current costs and returns. However, it may be possible to make native shrubs a profitable investment attractive to farmers through interventions aimed at reducing seedling cost and increasing carbon income. Such interventions may include supporting seedlings production, offering grants and subsidies for native shrubs establishment and augmenting income from native shrubs through biodiversity credits and premium carbon prices.

Further research is required to determine the preference and intake of browsable native shrubs by sheep, identify beneficial and detrimental non-nutritive compounds that can be present in these shrubs, and compare the nutritional composition, biomass, and carbon stock across different agroclimatic zones in New Zealand. In addition, the bioeconomic model can be improved by widening cash flows for native shrubs and radiata pine and including a module to estimate the carbon footprint for interventions to be compared.

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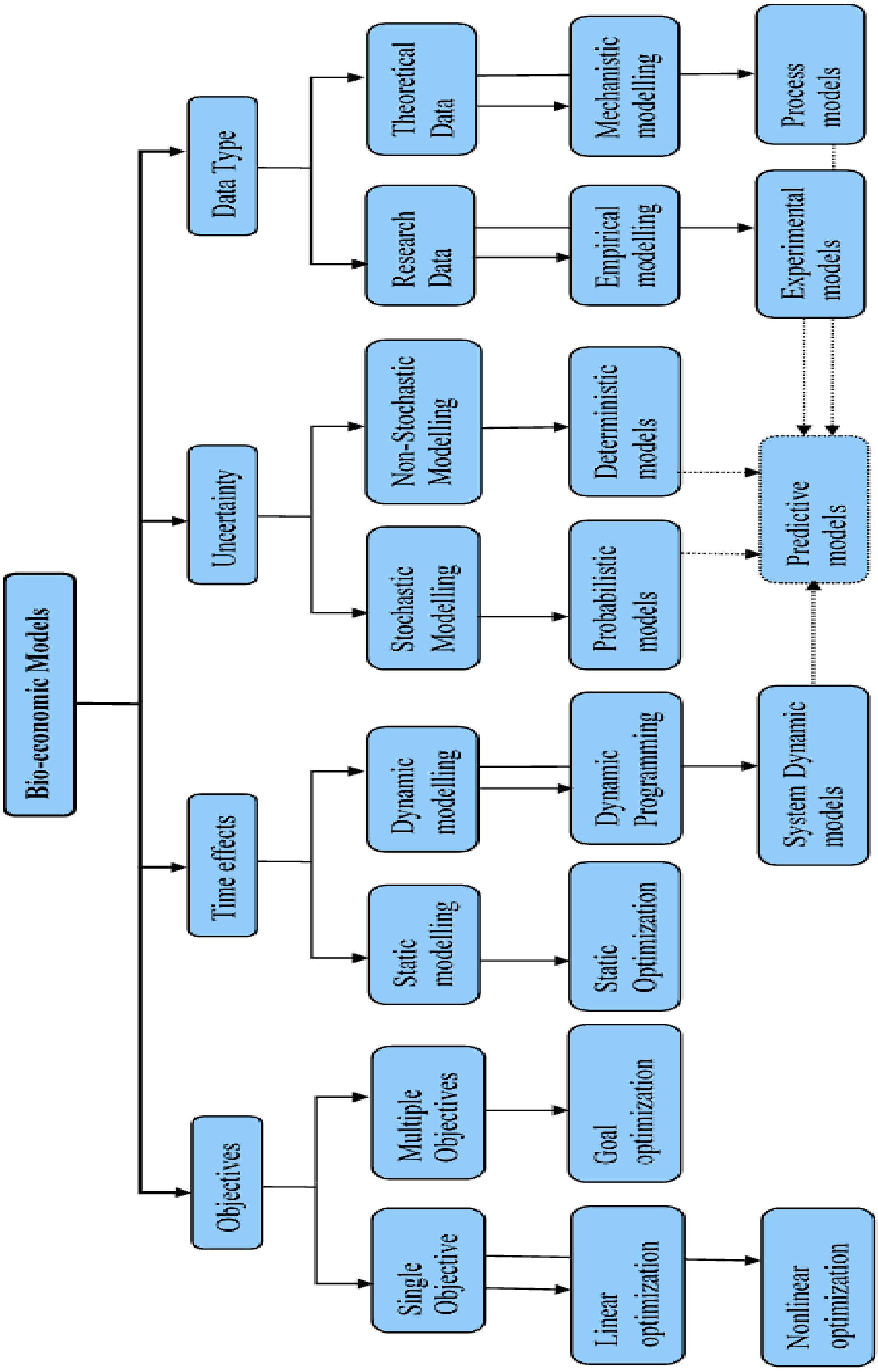
Appendices

Appendix 1. Approaches and types of bioeconomic models (Source. Castro et al. (2018))



Appendix 2. Supplementary results for *in vitro* fermentation products expressed in digested dry matter (DDM)

Supplementary Table 35. pH, total volatile fatty acids (VFA) in millimoles (tVFA, mM) from digested dry matter, percentage of respective VFA (Acetate, Propionate, Isobutyrate, Butyrate, Isovalerate, Valerate, %), ratio of Acetate to Propionate (A:P) and microbial biomass in milligram per gram of digested dry matter (MBM, mg/g DDM) for leaf and stem for native (Coprosma robusta, Griselinia litoralis, Hoheria populnea and Pittosporum crassifolium) and an exotic (*Salix schwerinii*) shrub species with potential use as fodder sources in New Zealand.

Shrub species	pH	Acetate	Propionate	Isobutyrate	Butyrate	Isovalerate	Valerate	Total VFA	A:P	MBM
					Leaf					
Coprosma robusta	6.57^{b}	63.1^{a}	22.2^{c}	0.15^{b}	13.8^{a}	0.11^{b}	0.69	30.9^{b}	2.9^{a}	114.7^{c}
Griselinia litoralis	6.57^{b}	61.2^{ab}	23.8^{c}	0.00^{c}	15.1^{a}	0.00^{b}	0.63	43.7^{a}	2.6^{a}	127.1^{bc}
Hoheria populnea	6.62^{ab}	62.7^{a}	25.0^{bc}	0.38^{a}	10.4^{b}	0.58^{a}	0.89	27.1^{b}	2.5^{a}	117.4^{bc}
Pittosporum crassifolium	6.57^{b}	57.6^{b}	27.6^{b}	0.33^{a}	13.1^{a}	0.52^{a}	0.92	43.2^{a}	2.1^{b}	169.2^{b}
Salix schwerinii	6.70^{a}	58.1^{b}	33.9^{a}	0.00^{c}	7.9^{c}	0.11^{b}	0.75	8.2^{c}	1.7^{b}	291.6^{a}
Pooled SE	0.027	0.98	0.73	0.033	0.57	0.062	0.070	1.29	0.09	12.18
					Stem					
Coprosma robusta	6.66	60.4^{ab}	25.0	0.00^{b}	14.2^{a}	0.00	0.74^{ab}	27.0^{ab}	2.5	128.0^{bc}
Griselinia litoralis	6.67	54.7^{b}	27.7	0.04^{b}	17.6^{a}	0.09	0.82^{a}	22.1^{b}	2.0	73.0^{c}
Hoheria populnea	6.66	55.8^{b}	27.9	0.29^{a}	15.1^{a}	0.38	1.03^{a}	33.6^{a}	2.0	118.7^{c}
Pittosporum crassifolium	6.67	53.3^{b}	31.9	0.09^{ab}	13.9^{a}	0.32	0.84^{a}	32.9^{a}	1.8	185.3^{b}
Salix schwerinii	6.71	68.6^{a}	25.9	0.00^{b}	7.7^{b}	0.00	0.29^{b}	19.7^{b}	2.7	295.8^{a}
Pooled SE	0.013	2.04	2.08	0.054	1.39	0.091	0.115	2.38	0.22	13.46

VFA, A:P and MBM with different superscripts in a column for the sample type are different at $p< 0.05$. Sample VFA value of 0.00 indicate the VFA was undetectable.

Appendix 3. Supplementary results for *in vitro* fermentation gas produced expressed in digested dry matter (DDM)

Supplementary Table 36. Native shrubs (*Coprosma robusta*, *Griselinia litoralis*, *Hoheria populnea* and *Pittosporum crassifolium*) and an exotic (*Salix schwerinii*) shrub species carbon dioxide (CO_2) and methane (CH_4) gas production in milliliters per gram of digested dry matter (mL/g DDM) and green house carbon dioxide equivalent (CO_2 Eq) in grams per gram of digested dry matter (g/g DDM) from the leaf and stem

Species	$mLCO_2$ /gDDM	$mLCH_4$ /gDDM	gCO_2 Eqv /gDDM
	Leaf		
Coprosma robusta	86.1^{a}	51.8^{a}	0.870^{a}
Griselinia littoralis	84.3^{ab}	48.5^{a}	0.852^{a}
Hoheria populnea	72.0^{b}	42.3^{a}	0.741^{a}
Pittosporum crassifolium	90.2^{a}	48.0^{a}	0.858^{a}
Salix schwerinii	35.3^{c}	17.7^{b}	0.316^{b}
SE	3.16	2.20	0.04
	Stem		
Coprosma robusta	75.0^{a}	41.9	0.719^{a}
Griselinia littoralis	80.3^{a}	40.4	0.703^{a}
Hoheria populnea	84.8^{a}	43.3	0.752^{a}
Pittosporum crassifolium	70.4^{a}	34.7	0.601^{ab}
Salix schwerinii	48.0^{b}	30.5	0.510^{b}
SE	4.62	3.80	0.04

Fermentation gas (CO_2 and CH_4) and carbon dioxide equivalent (CO_2 Eq) with different superscripts in a column for the sample type are different at $p < 0.05$.

Appendix 4. Chapter 3 Statement of Contribution

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UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	James Chege Wangui
Name/title of Primary Supervisor:	Dr Sarah Pain

In which chapter is the manuscript /published work: 3

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Wangui, J.C.; Kenyon, P.R.; Tozer, P.R.; Millner, J.P.; Pain, S.J. Bioeconomic Modelling to Assess the Impacts of Using Native Shrubs on the Marginal Portions of the Sheep and Beef Hill Country Farms in New Zealand. Agriculture 2021, 11, 21.

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- The name of the journal:
- The percentage of the manuscript/published work that was contributed by the candidate:
- Describe the contribution that the candidate has made to the manuscript/published work:

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Candidate's Signature:	James WANGUI Digitally signed by James WANGUI Date: 2023.04.26 10:58:15 +12'00'
Date:	26-Apr-2023
Primary Supervisor's Signature:	Sarah Pain Digitally signed by Sarah Pain DN: cn=Sarah Pain, c=NZ, o=Massey University, ou=SAE SVS, email=s.j.pain@massey.ac.nz Reason: I agree to the terms defined by the placement of my signature on this document Location: Palmerston North New Zealand Date: 2023.05.08 10:21:21 +12'00'
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Appendix 5. Chapter 5 Statement of Contribution

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We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	James Chege Wangui
Name/title of Primary Supervisor:	Dr. Sarah Pain

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Candidate's Signature:	James WANGUI Digitally signed by James WANGUI Date: 2023.04.26 11:03:29 +12'00'
Date:	26-Apr-2023
Primary Supervisor's Signature:	Sarah Pain Digitally signed by Sarah Pain DN: cn=Sarah Pain, c=NZ, o=Massey University, ou=SAE SVS, email=s.j.pain@massey.ac.nz Reason: I agree to the terms defined by the placement of my signature on this document Location: Palmerston North New Zealand Date: 2023.05.08 10:20:25 +12'00'
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