A kānuka silvopastoral system in New Zealand hill country

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To give your sheep or cow a large, spacious meadow

is the way to control him

Shunryu Suzuki

Abstract

Soil erosion, water quality issues, low production and climate change are some of the current challenges facing land managers and farmers in New Zealand hill country. 'Tree-pasture' silvopastoral systems that build soil resources could be integral land management practices for mitigating these issues and improving the health and production of these systems. Silvopastoral trees are already planted in New Zealand, although primarily used as soil conservation trees. Nevertheless, there are many other potentially facilitative effects of silvopastoral systems on other under researched silvopastoral outcomes. Researching these is vital for realising the full potential of silvopastoralism in New Zealand.

The native genus kānuka (*Kunzea* spp.) in New Zealand has the potential to form intergenerational and multifunctional silvopastoral systems that build soil resources and positively impact pasture production. This is because of the genus's potentially advantageous bio-physical tree attributes, such as its longevity, potentially reduced competition for soil water and nutrients compared to faster-growing and more resource intensive trees typically planted in hill country, and evergreen nature, potentially influencing livestock behaviour and soil organic matter return to the soil. Despite being locally very common in New Zealand hill country, this study is the first to measure the influence of kānuka silvopastoral trees on the pastoral environment at field scale.

The study begins by presenting a novel framework that links bio-physical tree attributes to a wide range of silvopastoral outcomes. Poplar (*Populus* spp.), the most commonly planted soil conservation tree in New Zealand hill country, and kānuka, are then reviewed as silvopastoral trees within this framework. This process clearly conveyed the complexity of silvopastoral systems and highlights that there may be potential for kānuka to positively impact many silvopastoral

outcomes such as longevity, pasture production, livestock welfare, biodiversity conservation and carbon sequestration.

The study then investigated the impact of kānuka on pasture production and pasture stability, soil condition and surface runoff and sediment and nutrient losses within a kānuka silvopastoral system. At two sites over two years, there was on average 107.9% more pasture production under kānuka trees compared to open pasture. This pasture production increase was associated with significantly greater Olsen-phosphorus, potassium and porosity. Soil moisture was similar between kānuka pasture and open pasture positions. The improvements to the agricultural environment were hypothesised to be because of livestock excreta deposition under the trees in the sheltered tree environment and tree litterfall.

The increased pasture production under the trees was the result of trees facilitating the growth of a few dominant and competitor pasture functional groups via the mass ratio effect such as perennial ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerata*), soft brome (*Bromus hordeaceus*) and barley grass (*Critesion murinum*). Moreover, despite reduced species richness and functional richness in kānuka pasture, there was evidence that pasture stability was maintained under the trees because functional evenness and functional dispersion was statistically similar in kānuka pasture and open pasture, and the functional groups that grew had mixed (cocksfoot) or annual (soft brome and barley grass) survival strategies. This indicates that kānuka has the potential to increase pasture production sustainably by not negatively impacting the pasture's response to stress.

There was 53.8 mm annual surface runoff in kānuka pasture and 7.5 mm in open pasture, despite the improved soil conditions in kānuka pasture. Moreover, sediment and nutrient losses were 10–100 times greater in kānuka pasture. Sediment and nutrient losses were a function of surface runoff, and these differences were hypothesised to be because significantly less pasture biomass was present under the trees, decreasing surface runoff attenuation. The pasture biomass difference was likely because of livestock preferentially grazing the pasture under kānuka because of the sheltered environment and good condition pasture. This suggests that a choice between good condition pasture under trees and poor condition pasture away from trees can lead to negative impacts in terms of sediment and nutrient management under isolated silvopastoral trees.

Overall, this study shows that tree configuration is a fundamental aspect in silvopastoral systems, and gives evidence that pasture biomass under silvopastoral trees is important for mitigating surface runoff and sediment and nutrient losses. The improved pasture production and pasture species composition under kānuka, in conjunction with the other potential environmental and cultural benefits of a kānuka silvopastoral system identified in the framework, shows that this genus may have potential to transform hill country landscapes by adding economic, environmental and cultural value to New Zealand farms. Nevertheless, because of the limitations of this study, such as the potential impact of site specific conditions and compounded livestock effects, more research is required to provide a full evaluation of the potential of kānuka silvopastoral systems in New Zealand hill country.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

AIC	Akaike information criterion
ANOVA	Analysis of variance
Asl	Above sea level
Ca	Calcium
CEC	Cation exchange capacity
CVA	Canonical variate analysis
Dicots	Dicotyledons
DRP	Dissolved reactive phosphorus
EDF	Effective degrees of freedom
FD	Functional diversity
FDis	Functional dispersion
FEve	Functional evenness
FRic	Functional richness
GAM	Generalised additive model
GLM	Generalised linear model
GDMP	Green dry matter production
HFA	High fertility annual grasses
k	knots
K	Potassium
LF	Low fertility tolerant grasses
LI	Light interception
LP	Low presence
Mg	Magnesium
MFS	Medium fertility species
N	Nitrogen
Na	Sodium
NZU	New Zealand Unit
P	Phosphorus

PAR	Photosynthetically active radiation
REML	Restrictive maximum likelihood estimates
S	Sulphur
TKN	Total kjeldahl nitrogen
VSM	Volumetric soil moisture

Chapter 1 Introduction

Tree-pasture 'silvopastoral' systems are used in pastoral land to make landscapes more ecologically complex in an attempt to increase farm production and resource-use efficiency, provide a range of ecosystem services and reduce landscape degradation (Nair, 1993; Nair et al., 2022; Young, 1989). How silvopastoral systems impact farm production is a central part of their function as a primary role of agricultural land is sustainable production. Silvopastoral trees have the potential to increase soil organic matter (Howlett et al., 2011; Rossetti et al., 2015) and nutrient (Gallardo, 2003; Marañón et al., 2009) and water availability (Bahamonde et al., 2009; Joffre and Rambal, 1993; Peri, 2005), which can result in trees increasing pasture production under their canopies (Belsky et al., 1993; Callaway et al., 1991; Frost and McDougald, 1989; Moreno, 2008; Peri, 2005).

New Zealand hill country is one agricultural region that could benefit from greater use of silvopastoralism. It is a region that is defined as having steep or hilly land (> 15°), an altitude < 1000 m asl and pastoral farming as its main land use (sheep, cattle and deer) (Dodd et al., 2016). Low-intensity sheep and beef farming in New Zealand is an economically important industry (Beef + Lamb, 2020a, 2020b; Kemp and López, 2016). However, pasture production in hill country is limited predominantly by slope and rainfall through impacts on water availability and soil conditions (López et al., 2003b; Zhang et al., 2005). For instance, pasture production on medium (13–25°) and high (> 25°) slope classes have been shown to be 54% and 68% less than low (< 13°) sloped classes, respectively (López et al., 2003b). Moreover, there are many environmental challenges associated with farming on hill country, in terms of soil erosion, water quality issues, climate change mitigation and bird biodiversity (Basher, 2013; Dominati et al., 2019; McDowell and Wilcock, 2008; Ministry for the Environment, 2021).

As one example, New Zealand hill country experiences high levels of sediment and nutrient losses. McDowell and Wilcock (2008) found average losses of 11 kg ha^{-1} yr^{-1} for total-nitrogen (total-N), 1.3 kg ha^{-1} yr^{-1} for total-phosphorus (total-P) and 1156 kg ha^{-1} yr^{-1} for suspended sediment in sheep and cattle catchments mainly in hill country. It has been estimated that 77% of New Zealand's national loads of N, P, sediment and *Escherichia coli* come from low-order streams, which are normally in hill country (Fuller, 2008; McDowell et al., 2017). There is increasing pressure on farmers in terms of national policy to mitigate water quality issues resulting from these losses (McDowell et al., 2017; Ministry for the Environment, 2021).

Silvopastoral trees that build soil resources and increase infiltration rates and soil moisture could potentially be used to increase the production of medium and high sloped areas of hill country, and reduce surface runoff and associated sediment and nutrient losses. This is in addition to the other benefits silvopastoral trees could provide in terms of biodiversity conservation (Boffa Miskell Limited, 2017; Dominati et al., 2019; Williams and Karl, 2002), animal welfare (Blackshaw and Blackshaw, 1994; Pollard, 2006), livestock grazing time and live weight increases (Betteridge et al., 2012; Blackshaw and Blackshaw, 1994; Pollard, 2006; Soares et al., 2009), carbon sequestration (Guevara-Escobar et al., 2002) and slope stability (Douglas et al., 2013; Spiekermann et al., 2022, 2021). Silvopastoralism could therefore become vital land management systems for overcoming many of the environmental challenges currently associated with farming in New Zealand hill country.

Silvopastoralism is already used in New Zealand hill country, although the primary purpose of planted trees is soil conservation (Benavides et al., 2009; Wilkinson, 1999). The most commonly planted silvopastoral trees are poplar (*Populus* spp.) and willow (*Salix* spp.), and both have been shown to be effective soil conservation trees in terms of reducing landslides compared to open pasture (Douglas et al., 2013; McIvor et al., 2015; Spiekermann et al., 2021).

Nevertheless, all published studies on both these genera have reported a negative relationship with pasture production (Benavides et al., 2009; Devkota et al., 1997; Douglas et al., 2001; Gilchrist et al., 1993; Guevara-Escobar et al., 2007; Miller et al., 1996; Wall, 2006). Moreover, past studies did not find consistent evidence that the most commonly planted of these, poplar, increases soil P, N or organic matter compared to open pasture (Guevara-Escobar et al., 2002; Wall, 2006). Other studies have also measured pasture production under different silvopastoral trees, such as radiata pine (*Pinus radiata* D. Don) (Benavides et al., 2009), Italian grey alder (*Alnus cordata* (Loisel.) Duby) (Devkota et al., 2009), Australian blackwood (*Acacia melanoxylon* R. Br.) (Power et al., 1999) and eucalyptus (*Eucalyptus* spp.) (Power et al., 1999). However, as far as I am aware, there have been no published studies that have measured an overall increase in pasture production under mature silvopastoral tree canopies compared to open pasture in New Zealand.

Expanding research to alternative tree species and genera is integral for finding silvopastoral trees that may increase soil resources and have a facilitative relationship with pasture production in New Zealand hill country. If trees can be found that improve soil resources and increase pasture production, this could incentivise the adoption of silvopastoralism in hill country. Incentivising tree planting could also lead to many other environmental benefits of planting trees on farms, such as the potential reduction in surface runoff and associated sediment and nutrient losses, slope stability, carbon sequestration, biodiversity conservation and livestock welfare. Silvopastoral systems would therefore become innovative land management practices for overcoming environmental and production agricultural trade-offs, creating resilient, diverse, and productive hill country landscapes.

Furthermore, focusing research on silvopastoral trees that potentially have facilitative effects on outcomes beyond slope stability could reinforce the multifunctional nature of silvopastoral systems. Silvopastoralism research could therefore highlight opportunities for mitigating many of the current environmental challenges farmers face in hill country and help provide transformative impacts to New Zealand farms.

Another genus that grows readily in New Zealand hill country is the native kānuka (*Kunzea* spp.) (Bergin et al., 1993; Spiekermann et al., 2021). Kānuka is a silvopastoral tree that already grows in hill country, but to date, has not been considered as a viable silvopastoral option on New Zealand farms. As is explored in Chapter 2, kānuka has contrasting bio-physical attributes to poplar, that could mean it has a facilitating relationship with pasture production because of its influences on the soil and livestock. If kānuka can positively influence soil organic matter and soil fertility, this may also have important implications on soil stability and infiltration rates, and thus the reduction of surface runoff and associated sediment and nutrient losses. Furthermore, because of the tree attributes that are explored in Chapter 2, the genus is highly likely to have positive impacts on additional outcomes such as tree management, longevity, animal welfare, carbon sequestration, biodiversity conservation and slope stability. Nevertheless, there have been no published studies examining the interaction of kānuka as a silvopastoral tree in New Zealand hill country at field scale.

1.1 Objectives and hypotheses

The overarching aim of this thesis is to inform change in New Zealand hill country, to unlock opportunities for silvopastoral trees to provide production and environmental benefits to New Zealand hill country farms, thus overcoming production and environmental trade-offs. The thesis will explore this by reviewing the potential impact of a kānuka silvopastoral system on a wide range of silvopastoral outcomes in a novel framework created for holistically reviewing silvopastoral trees (Chapter 2), in addition to researching the following objectives:

Objective 1: measure how a kānuka silvopastoral system impacts pasture production compared to open pasture, and identify and discriminate the variables that contribute to pasture production differences between kānuka pasture and open pasture.

Hypothesis 1: kānuka silvopastoral trees positively influence pasture production compared to open pasture in New Zealand hill country by increasing the availability of water and nutrients.

Kānuka has several bio-physical attributes that differ from poplar, which could mean it increases pasture production under its canopy. Compared to poplar, these attributes include a lower and more sheltered evergreen canopy, which is potentially more attractive to livestock and could result in more nutrient transfer via dung and urine to the tree pasture environment, leading to a build-up of organic matter under the tree. Litterfall is year-round and leaves are bitter, which may reduce livestock uptake of leaf fall and increase organic matter addition into the soil. Kānuka most likely grows slower than poplar (Boffa Miskell Limited, 2017; McIvor et al., 2011; Phillips et al., 2014), which means it should use less water and nutrients during establishment. Finally, poplar has a high water use (Guevara-Escobar et al., 2000; Wilkinson, 1999; Wullschleger et al., 1998), so this is likely to put further strain on water resources for pasture growth when the tree is mature compared to kānuka. Thus, pasture production should be improved under kānuka trees compared to open pasture because of greater water and nutrient availability.

Objective 2: using a functional ecology perspective, understand the ecological mechanisms by which a kānuka silvopastoral system impacts pasture production, and measure how pasture stability is affected by kānuka trees compared to open pasture in New Zealand hill country.

Hypothesis 2: kānuka silvopastoral trees increase the growth of more productive pasture functional groups under their canopy, and at least maintain pasture stability compared to open pasture in New Zealand hill country.

Pasture production in hill country can be a direct result of pasture species composition changes (López et al., 2006; Nicholas, 1999). Therefore, if kānuka can positively impact pasture production by increasing the availability of water and nutrients, this will facilitate the growth of more desirable and productive functional groups such as perennial ryegrass (*Lolium perenne* L.) and high fertility grasses (López et al., 2006; Nicholas, 1999). Trees will also maintain or increase pasture stability, in terms of the pasture's impact to stress (Frank and McNaughton, 1991; Grime, 1989), by facilitating the growth of more productive species that are also stress tolerators (e.g. cocksfoot (*Dactylis glomerata* L.)) (Sankaran and McNaughton, 1999; Tracy and Sanderson, 2004).

Objective 3: quantify how a kānuka silvopastoral system impacts surface runoff and sediment and nutrient losses in New Zealand hill country.

Hypothesis 3: kānuka silvopastoral trees reduce surface runoff and sediment and nutrient losses compared to open pasture in New Zealand hill country.

If kānuka increases soil organic matter and soil fertility, this will result in more stable soils that are less prone to sediment and nutrient loss in surface runoff events (Ekwue, 1990; Zhu et al., 2020). Soil with more organic matter will increase the water holding capacity and porosity of the soil, increasing the time until soil saturation and infiltration rates, and reducing the amount of surface runoff (McLaren and Cameron, 1996). Moreover, the evergreen canopy of kānuka will cause rainfall interception in winter, reducing throughfall compared to open pasture, which should impact surface runoff amounts. Finally, if surface runoff is reduced under the trees, this will result in less sediment and nutrient loss as these processes have been shown to be a function of increasing surface runoff (Chen et al., 2018; Zhou et al., 2016).

1.2 Thesis outline

There are many theses, review papers and books that have summarised the empirical effects of silvopastoral trees on the soil, pasture and water (Benavides et al., 2009; Devkota, 2000; Guevara-

Escobar, 1999; Hussain, 2009; Joshi, 2000; Marañón et al., 2009; Nair et al., 2022; Wall, 2006; Young, 1989). Chapter 2 presents a literature review in an alternate form, which is a review paper that develops a novel framework for reviewing silvopastoral trees globally by relating tree bio-physical attributes to silvopastoral outcomes, and reviews past literature for kānuka and poplar within this framework. The synthesis of this review then compares how the different bio-physical attributes of kānuka and poplar may impact their potential as silvopastoral trees over a wide range of silvopastoral outcomes. This chapter has been published as a review paper in the journal **Land** (Mackay-Smith, T.H., Burkitt, L., Reid, J., López, I.F., Phillips, C., 2021. A Framework for Reviewing Silvopastoralism: A New Zealand Hill Country Case Study. Land 10, 1386. https://doi.org/10.3390/land10121386).

Chapter 3, chapter 4 and chapter 5 are standalone papers which address each of the three research hypotheses. Chapter 3 reports on the impact of kānuka on pasture production and nutrient and water availability, Chapter 4 measures the ecological mechanisms for how kānuka impacts pasture production and stability outcomes, and Chapter 5 measures the impact of kānuka on surface runoff and sediment and nutrient losses. As the thesis is being submitted as a Thesis by Publication and all three papers are linked to one broader study undertaken at two sites, there is some repetition in the descriptive sections of the introductions and methods of the three papers.

At the time of thesis submission, all papers are either published or are about to be submitted to Q1 journals. Chapter 3 will be submitted to **Agronomy**, Chapter 4 will be submitted to the **Journal of Agronomy and Crop Science**, and Chapter 5 has been published in **Catena** (Mackay-Smith, T.H., Burkitt, L.L., López, I.F., Reid, J.I., 2022. The impact of a kānuka silvopastoral system on surface runoff and sediment and nutrient losses in New Zealand hill country. CATENA 213, 106215. https://doi.org/10.1016/j.catena.2022.106215).

Chapter 6 ends the thesis by examining whether the results are in accordance with the hypotheses, and discusses the novel findings of the thesis and how the results of each chapter link together.

It then explores the implications of these findings in the context of New Zealand hill country and how the results challenge the current perception of silvopastoral trees in New Zealand agricultural landscapes. Finally, it suggests important future research that is required to thoroughly assess the potential of kānuka more fully as a silvopastoral tree in New Zealand hill country.

Chapter 2 A framework for reviewing silvopastoralism: a New Zealand hill country case study

This chapter presents a literature review in an alternative form, which creates a novel framework that links silvopastoral tree bio-physical attributes to silvopastoral outcomes. The paper then reviews and compares poplar, the most commonly planted silvopastoral tree in New Zealand hill country, and kānuka, as silvopastoral trees within the framework.

This chapter has been published as:

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land

Dr. Chris Phillips from Manaaki Whenua – Landcare Research provided valuable input to this paper because of his previous work with poplar.

2.1 Introduction

Agroforestry is a land use where woody perennials (typically trees) are deliberately integrated into agricultural land (pastoral or arable), and there is an ecological interaction between the woody perennial and the agricultural component of the system (positive or negative) (Nair, 1993). Silvopastoral systems are a type of agroforestry system where trees are integrated into a pastoral system (Nair, 1993). Silvopastoral systems are commonly adopted in environmentally sensitive areas to mitigate landscape degradation (Basher et al., 2016; Kemp et al., 2018; Peri et al., 2016b). Many of these are hilly or mountainous, and include for example the poplar (*Populus* spp.) and willow (*Salix* spp.) silvopastoral systems in New Zealand hill country (Kemp et al., 2018), the ñire (*Nothofagus antarctica* (G.Forst.) Oerst.) system of Patagonia (Peri et al., 2016b), and the oak (*Quercus* spp.) silvopastures of California (Ratliff et al., 1991), the Indian Himalayas (Kumar et al., 2018) and Spain (the *dehesa* system) (Joffre et al., 1999).

Silvopastoral systems are inherently complex and result in many ecological, economic and cultural outcomes within the agricultural system. In order that silvopastoral systems are fully understood and appreciated, it is important that research spans as many of these outcomes as possible. If only specific outcomes are studied, research or tree planting choices may be biased towards these narrowly selected outcomes, and other potential benefits may be overlooked or underappreciated. Moreover, if the maximum benefits of silvopastoral tree plantings are to be realised and plantings are to be justified, their full range of known benefits and costs must be compared.

As an example of this, in the hill country of New Zealand (an area characterised by hill and steep land (> 15°), being below 1000 m asl and pastoral farming as its main land use) (Dodd et al., 2016), there is a narrow research focus on the principal silvopastoral tree genera that are planted (poplar and willow). The focus is on pasture production, soil conservation and establishment ease (Basher, 2013; Benavides et al., 2009; Kemp et al., 2018), with soil conservation value and establishment ease primarily informing planting decisions.

These genera have been shown to be highly effective as soil conservation trees (Douglas et al., 2013; McIvor et al., 2015; Spiekermann et al., 2021), and can be planted easily as 2–3 m unrooted coppiced poles with sheep and small cattle grazed immediately after establishment (Kemp et al., 2018; Phillips et al., 2014). Nevertheless in hill country, as far as we are aware, there has been no research on silvopastoral functions such as biodiversity conservation value, wind run reductions, shelter value comparison between species or genera, impacts on catchment discharge rates (in low density (20–200 tree ha^{-1}) systems), among others that will be highlighted in this paper. Historically, other genera have been overlooked because only a few factors have been considered in planting decisions, even though many alternative species may be more suitable in certain situations, or their overall benefits greater than those of poplar or willow.

Von Carlowitz (1986) presented a framework, which itself was adapted and published by Wood (1990), that provides a useful way of looking at the multitude of outcomes within agroforestry systems. The authors split trees into their bio-physical attributes and related these to 'performance' in an agroforestry system (Table 2.1). Dividing trees into their bio-physical attributes is useful because it helps show why a tree may be contributing to a positive or negative silvopastoral outcome. This means that alternative trees can be selected based upon their attributes, and silvopastoral species or genera research or tree planting choice can then be optimised for specific silvopastoral systems, based upon a system's outcome needs.

However, the framework presented by Von Carlowitz (1986) and Wood (1990) is focused on agroforestry rather than silvopastoral systems, and takes a narrow tree performance view on silvopastoral system outcomes, therefore missing their holistic nature. Because of these primary reasons, and others that will be explored in the next section, this paper presents a new framework, that like Von Carlowitz (1986) and Wood (1990) identifies and links bio-physical attributes to system outcomes, but does so for a silvopastoral system, and expands the outcomes to account holistically for the full range of known silvopastoral outcomes. Section 2.2 will present this framework, and explain in more detail how it differs from the one formulated by Von Carlowitz (1986) and Wood (1990), and why these changes are necessary.

Table 2.1. An agroforestry framework relating tree attributes to 'performance' in an agroforestry system created by Von Carlowitz (1986), that was adapted and published by Wood (1990). Copyright © 1990 John Wiley & Sons, Inc.

Tree attributes	Relationship to performance in agroforestry systems
Height	Ease of harvesting leaf, fruit, seed and branchwood; shading or wind effects
Stem form	Suitability for timber, posts and poles; shading effects
Crown size, shape, and density	Quantity of leaf, mulch and fruit production; shading or wind effects
Multistemmed habit	Fuelwood and pole production; shading or wind effects
Rooting pattern (deep or shallow, spreading or geotrophic)	Competitiveness with other components, particularly resource sharing with crops; suitability for soil conservation
Physical and chemical composition of leaves and pods	Fodder and mulch quality; soil nutritional aspects
Thorniness	Suitability for barriers or alley planting
Wood quality	Acceptability for fuel and various wood products
Phenology (leaf flush, flowering and fruiting) and cycle (seasonality)	Timing and labor demand for fruit, fodder and seed harvest; season of fodder availability; barrier function and windbreak effects
Di = or monoeciousness	Sexual composition of individual species in community (important for seed production and pollen flow)
Pest and disease resistance	Important regardless of function
Vigor	Biomass productivity, early establishment
Site adaptability and ecological range	Suitability for extreme sites or reclamation uses
Phenotypic or ecomorphological variability	Potential for genetic improvement, need for culling unwanted phenotypes
Response to pruning and cutting management practices	Use in alley farming, or for lopping or coppicing
Possibility of nitrogen fixation	Use in alley farming, planted fallows, or rotational systems

We believe that our new framework will appeal to multiple groups. Firstly, it provides a standardised methodology for the research community to review silvopastoral research, and to identify research priorities that will improve understanding of specific silvopastoral systems. Additionally, it will enable researchers to review trees in relation to all their known potential outcomes, and reduce research biases for specific outcomes, as has been the case in New Zealand hill country to date. The second half of this paper will illustrate the framework being used in this way, and will compile current knowledge for poplar, the most commonly planted and researched silvopastoral tree genus in New Zealand, and kānuka (*Kunzea* spp.), a genus that has received little attention in a hill country silvopastoral context. Based on the framework, the genera will be assessed, reviewed and compared across their full range of known benefits and costs.

Secondly, the framework will provide an opportunity for practitioners and land managers to see the multitude of known interactions within a silvopastoral system. It will also clearly highlight the holistic nature of silvopastoral systems, and reduce the focus only on specific outcomes, as has been the case in New Zealand hill country. When trees have been reviewed and compared, this comparison can then be used by land managers when deciding which tree may be best for their specific situation, depending on their requirements. Finally, in time, a unit of value could be added to the different outcomes in the framework. This would allow researchers, land managers and landowners to quantifiably discriminate which tree may be best for a specific situation. This, however, is beyond the scope of this paper.

Silvopastoral systems are complex, comprising multiple inter-related components. A framework that captures this complexity is fundamental to ensure that the full potential of silvopastoral trees may be researched, realised and appreciated. The framework will be a valuable tool for multiple groups when selecting and researching silvopastoral trees, especially in hilly or mountainous regions.

2.2 A Framework for assessing silvopastoralism

Figure 2.1 shows the new framework for silvopastoralism, which outlines all the known interactions within a silvopastoral system between a tree's bio-physical attributes and system outcomes. The following section explains in more detail how this new framework improves on the original framework created by Von Carlowitz (1986) and Wood (1990).

As Von Carlowitz (1986) and Wood (1990)'s framework was designed for agroforestry systems in general and not silvopastoral systems, the framework places little emphasis on the interactions fundamental to a silvopastoral system. These include interactions between trees and livestock, and between the grazing animals, soil and pasture.

Many environmental, management and cultural outcomes associated with silvopastoral systems are also lacking in the original framework. In the new framework outcomes are expanded to include the following environmental outcomes: 'water and nutrient gains or losses', 'biodiversity interactions (excluding livestock and the forage crop)', 'greenhouse gas implications' and 'longevity of the tree'; management outcomes: 'costs and ease of establishment', 'special qualities reducing livestock interactions with the tree', 'longevity of the tree' and 'ability to refine the tree form for improved silvopastoral outcomes'; and cultural outcomes: 'livestock shelter' ('livestock shelter' is a cultural outcome in terms of animal health reasons and a production outcome in terms of live weight increase reasons), 'cultural values' and 'aesthetics'.

In addition to outcomes, the new framework also includes additional attributes of specific relevance to hill country silvopastoral systems, including 'growth rate', 'establishment method (seedling, cutting, pole)' and 'water use'. In hill country, silvopastoral systems commonly need to be established as trees, so a tree's growth rate and establishment form is a key consideration in planting decisions. Moreover, the interaction between the tree and pasture in terms of water is also important, an attribute lacking in Von Carlowitz (1986) and Wood (1990)'s framework.

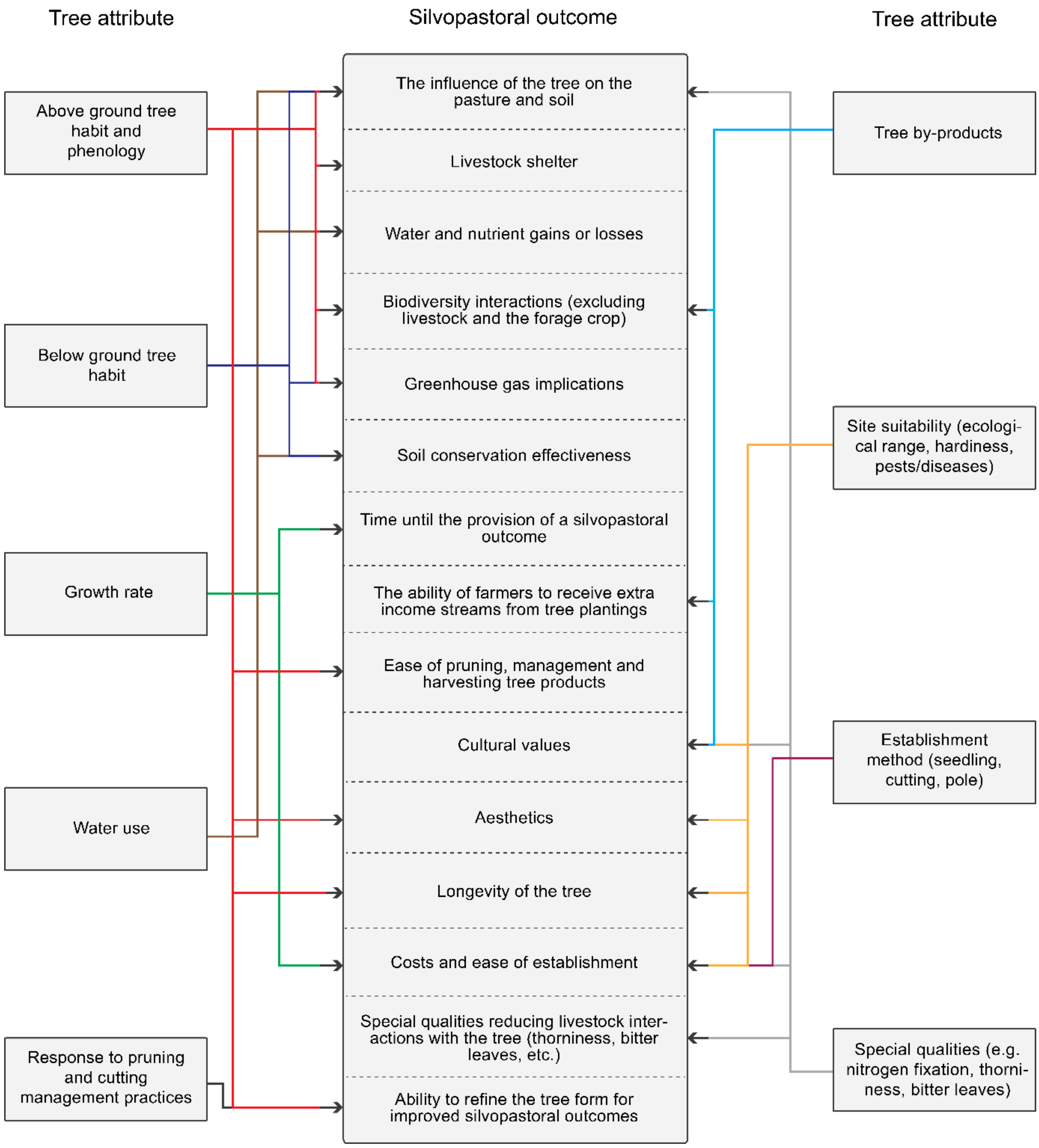


Figure 2.1. A framework of the interactions within a silvopastoral system between tree attributes and silvopastoral outcomes.

To improve Von Carlowitz (1986) and Wood (1990)'s framework, multiple attributes have been grouped into one attribute in the new framework. For example, the attributes 'height', 'stem form', 'crown size, shape and density', 'multistemmed habit', 'phenology (leaf flush, flowering and fruiting) and cycle (seasonality)' and 'Di = or monoeciousness' are encompassed into the broader attribute: 'above ground tree habit and phenology'. Moreover, 'pest- and disease-resistance', 'vigor', 'site adaptability and ecological range' and 'phenotypic or ecomorphological variability' are grouped to form one attribute: 'site suitability (ecological range, hardiness, pests/diseases)'.

Moreover, a 'special qualities' attribute was added to the framework so any unique tree qualities in other silvopastoral systems can be incorporated into the framework.

Von Carlowitz (1986) and Wood (1990)'s framework was primarily developed to inform the selection of trees for agroforestry systems. The new framework can also be used in this way, but we extend the use of our framework and use it to comprehensively collate research and knowledge on particular trees. Doing so in this paper clearly highlights the practical use of the framework to researchers for assessing and comparing silvopastoral trees.

2.3 Using the framework: a New Zealand hill country case study

The following section will illustrate how the framework can be used to review two silvopastoral systems and generate research priorities in a degraded, but economically important, hilly and mountainous region.

As definitions of New Zealand hill country vary (Dodd et al., 2016), so do area estimations, but one estimate of the area of hill country is 6.6 million ha (24.72% of New Zealand's land mass), with 5.2 million ha of this in pastoral farming (Figure 2.2) (Mackay, 2008). Much of this hill country is marginal agricultural land that was cleared of native forest, associated with reduced organic matter, nutrient levels and water holding capacities, resulting in many areas having a low production (López et al., 2003b). Due to the highly topographic and treeless nature of hill country, soil erosion and surface runoff discharge rates are high (Dodd et al., 2016).

These poor conditions have multiple ramifications for New Zealand. High sediment loads alter local floral and faunal streambed habitats (Dodd et al., 2016), reduce river clarity, and reduce the soil base of hill country farms. Nitrogen (N) and phosphorus (P) losses with sediment encourage algal growth (McDowell et al., 2009; Schindler et al., 2008), further degrading river habitats and the quality of water supplies (Ministry for the Environment, 2018). Furthermore, elevated surface water discharge results in elevated flood severity and risk (Krausse et al., 2001).

Figure 2.2. A typical North Island New Zealand hill country landscape 25 km northeast of Dannevirke, in the Manawatū-Whanganui region. Willows can be seen space-planted in pastures at the bottom of the slope directly beneath the photographer. The photograph was taken by the lead author.

2.3.1 Poplar and willow

The principal soil conservation intervention in New Zealand is tree planting, specifically aimed at the mitigation of shallow mass movement events (shallow landslides), earthflows and gully erosion (Basher et al., 2016; McIvor et al., 2015). Space-planted poplar and willow are the main genera grown, planted at densities that range from 20 trees ha^{-1} to 200 trees ha^{-1} (Benavides et al., 2009; Kemp et al., 2018). Afforestation is additionally used for soil conservation, in the form of exotic forestry plantations (principally radiata pine (*Pinus radiata* D. Don) at densities ~1200 trees ha^{-1}), native mānuka (*Leptospermum scoparium* J.R.Forst. & G.Forst.) plantations (~1200 trees ha^{-1}) for honey production, or native forest via unmanaged regeneration or native seedling establishment (Kemp et al., 2018).

Poplar and willow have been extensively researched, including reviews by Benavides et al. (2009), Kemp et al. (2018) and Basher et al. (2016). They have been shown to be highly effective as soil conservation trees (Douglas et al., 2013; McIvor et al., 2015; Spiekermann et al., 2021), and can be planted easily as 2–3 m unrooted coppiced poles protected by a plastic sleeve, with sheep and small cattle grazed immediately after establishment (Kemp et al., 2018; Phillips et al., 2014). Nevertheless, a 40-year tree life is recommended as branch breaking is common (Charlton et al., 2007), reducing the long-term soil conservation or carbon sequestration potential of each tree. Additionally, the negative effects of poplars on pasture growth are well established (Benavides et al., 2009; Kemp et al., 2018) and there is little evidence they improve soil properties beneath their canopies (Guevara-Escobar et al., 2002; Wall, 2006).

In terms of other species, Devkota et al. (2009) studied the canopy effect of Italian grey alder (*Alnus cordata* (Loisel.) Duby) on soil and pasture, and Australian blackwood (*Acacia melanoxylon* R.Br.) and eucalyptus (*Eucalyptus* spp.) have also been studied in the context of timber production, pasture production, soil properties and landslide mitigation (Douglas et al., 2013; Power et al., 2003, 1999; Thorrold et al., 1997). Many trees and shrubs have been researched for their potential use as fodder trees including research on poplar and willow (Kemp et al., 2001; McWilliam et al., 2005; Orsborn et al., 2003), as well as tree lucern (*Cytisus proliferus* L.f.), and saltbush (*Atriplex halimus* L.) (Logan and Radcliffe, 1985; Wills, 1990), among others (Logan and Radcliffe, 1985). Nonetheless, poplar and willow remain the dominant silvopastoral system in hill country because of their use as soil conservation trees, despite their constraints.

2.3.2 Kānuka

Kānuka is a native and successional genus that already grows in New Zealand hill country, and has many attributes (which will be explored in this review) that mean it has the potential to perform well as a silvopastoral tree. Kānuka has been split into 10 endemic New Zealand species (de Lange, 2014), although Heenan et al. (2021) provides evidence that questions this 10 species description. Nevertheless, as of 2021, 10 are still recognised. These 10 species occupy different ecological niches and geographical extents (de Lange, 2014). Seven of these species (*K. amathicola*, *K. ericoides, K. linearis, K. robusta, K. salterae, K. serotina, K. triregensis*) are trees that can reach a height greater than 10 m (de Lange, 2014), and are the most suitable for use in a silvopastoral system. Most people collectively refer to these species by their common name, kānuka. This paper will use the term kānuka and is specifically referring to the seven kānuka species which are greater than 10 m in height when growing in native forest.

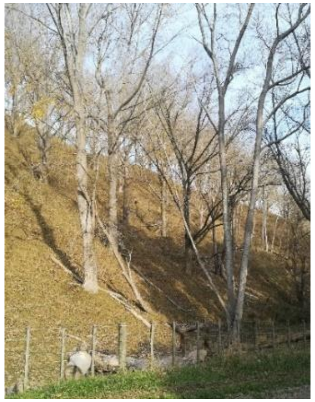
In most places, kānuka, along with mānuka and gorse (*Ulex europaeus* L.), are one of the first woody perennial species to colonise unmanaged pasture in New Zealand hill country (Rees and Hill, 2001; Williams and Karl, 2002). When kānuka grows on this unmanaged pasture, the predominant practice is to clear the kānuka to produce treeless pastures (Wilmshurst, 1997). However, this paper demonstrates that kānuka has many beneficial attributes in a silvopastoral system and that thinning instead of clearing higher density kānuka stands (Spiekermann et al., 2021), or even space-planting the tree on hill country pastures, should be encouraged.

2.3.3 Reviewing current knowledge for poplar and kānuka

Drawing on existing research and knowledge, poplar, the most commonly planted silvopastoral tree in hill country, and kānuka, are now reviewed and compared according to the framework tree attributes (Table 2.2) and system outcomes (Table 2.3). Information compiled in Table 2.2 and Table 2.3 arises from different sources. The first are visible factors, such as the heights of unmanaged trees growing in hill country. This is information in Table 2.2 that has no references.

The second are projected interactions that have been logically inferred based upon known tree attributes (e.g. an evergreen tree will reduce wind run in winter more than a deciduous tree). These are sections in Table 2.3 under the label *likely outcome* where there is *no evidence* for a specific outcome. The final source is literature, either peer-reviewed scientific research or reports. These are labelled as *evidence for* and *evidence against* in Table 2.3. Table 2.2 does not contain *evidence for* or *evidence against* descriptions because tree attributes themselves are not positive or negative, but it is the resultant outcomes that are positive or negative to the user of the silvopastoral system.

Table 2.2. Tree attributes for poplar (*Populus* spp.) and kānuka (*Kunzea* spp.) in a New Zealand hill country silvopastoral system. Tree attributes have been adapted from von Carlowitz (1986) and Wood (1990). The photographs were taken by the lead author.

Tree attribute	Poplar (*Populus* spp.) attribute	Priority research area	Kānuka (*Kunzea* spp.) attribute	Priority research area
Above ground tree habit and phenology	Current cultivars planted in the 1960s and 1970s are > 30 m in height. Crowns are large and uncompact. Older cultivars often have large branches extended; some are multistemmed. Newer cultivars have been developed which grow as a single, straighter stem. Deciduous. 	Yes - an understanding of the form of newer poplar cultivars when they are fully-grown would be informative.	When growing isolated in hill country, kānuka are 8–20 m in height. Compact crowns. Stems can be multi- or single-stemmed. Many branches when unmanaged. The form of kānuka varies with tree density, growing taller and thinning in higher densities. Evergreen. 	No

Tree attribute	Poplar (*Populus* spp.) attribute		Priority research area	Kānuka (*Kunzea* spp.) attribute		Priority research area
Below ground tree habit	For three 11.5-year-old poplar trees on a 17° hill country site at densities of 156 tree ha^{-1}, maximal lateral root extension ranged from 8–12 m.	McIvor et al. (2009, 2008)	No	Only kānuka growing in high density forest stands (~3000–16,000 stems ha^{-1}) have been studied. Fifteen 16-year-old trees growing at 12,800 stems ha^{-1} had a maximum root length of 4.5 m. Fifteen 32-year-old trees growing at 3,900 stems ha^{-1} had a maximum root length of 6.1 m.	Watson et al. (1999, 1997)	Yes – research on the root distribution of kānuka growing at typical hill country silvopastoral densities (20–200 tree ha^{-1}) is required.
	Mean tensile strength of 44.0 MPa (minimum: 11.1 MPa; maximum: 114.3 MPa).	Watson et al. (2008)				
	The total root length of a 9.5-year-old poplar tree was found to be 663.5 m with a root biomass of 17.9 kg.	McIvor et al. (2008)		Mean tensile strength of 34.1 MPa (minimum: 18.2 MPa; maximum: 75.8 MPa).	Watson and Marden (2004)	
	The lateral root extension, root biomass and total root length of ‘fully-grown’ poplar trees on hill country > 25.0° would be valuable.			In another high-density stand (3000 stems ha^{-1}), the total root length of one fully-grown kānuka tree 9.5 m in height was shown to be 123.2 m, have a root biomass without the stump of 11. 8 kg and a lateral root spread of 2.8 m.	Watson and O’Loughlin (1990)	

Tree attribute	Poplar (*Populus* spp.) attribute		Priority research area	Kānuka (*Kunzea* spp.) attribute		Priority research area
Growth rate	On a 21–35° slope, the mean height of 268 poplar poles was just under 3.0 m after 12 months, ~3.5 m after 24.0 months and ~5.3 m after 45.0 months. Start heights were not given by the authors so yearly growth rates could not be calculated.	Marden and Phillips (2013)	No	Initial growth rates are often 0.7–0.8 m $year^{-1}$ in sheltered and high fertility sites, and 0.4–0.5 m $year^{-1}$ in poorer sites. This data was collected from interviews, and was not stated to be quantitatively studied in the report.	Boffa Miskell Limited (2017)	Yes - quantitative information on growth rates in contrasting conditions, as well as at 20–200 tree ha^{-1} densities, is required.
	5.0-, 7.0- and 9.5-year-old trees had heights of 7.0, 9.5 and 13.3 m, respectively, on a 17.0° hill country site. This equates to a ~1.3 m $year^{-1}$ growth rate (accounting for the 1.4 m start height of the poles).	McIvor et al. (2008)				
Water use	Four trees were shown to have an average water use of 180.1 L day^{-1} during spring, which equated to 1.2 mm day^{-1}. One of these trees had a water use of 417.0 L day^{-1}.	Guevara-Escobar et al. (2000)	No			Yes – the water use of kānuka is unknown.

Tree attribute	Poplar (*Populus* spp.) attribute		Priority research area	Kānuka (*Kunzea* spp.) attribute		Priority research area
Response to pruning and cutting management practices	Responds well to pruning when the trees are young, as well as coppicing and pollarding.	Charlton et al. (2007)	No			Yes - the response to management is unknown.
Tree by-products	Wood – poplars can be pruned and harvested for timber. Fodder – leaves are excellent fodder for animals. Emissions trading scheme (ETS) – there is the potential for farmers to receive carbon credits (1 NZU = 1 tonne of sequestered CO_2) if the tree crown canopy is > 30% in each hectare.	Charlton et al. (2007) Kemp at al. (2018) Ministry for Primary Industries (2020)	Yes - research required to understand the density required to achieve a 30% canopy cover with poplar.	Wood – reported to be good firewood. Fodder – kānuka leaves are 0.5–2.5 cm, the tree doesn't have summer leaf flush as they are evergreen and the leaves are potentially bitter, so we tentatively suggest that the trees would be poor fodder quality. Honey – shown to have anti-bacterial, anti-viral, immunostimulatory and anti-inflammatory properties.	Boffa Miskell Limited (2017) e.g. Bloor (1992); Gannabathula et al. (2012); Lu (2013); Tomblin et al. (2014)	Yes - research required to understand the density required to achieve a 30% canopy cover with kānuka.

Tree attribute	Poplar (*Populus* spp.) attribute		Priority research area	Kānuka (*Kunzea* spp.) attribute		Priority research area
				Essential oil – kānuka essential oil has been shown to be an effective eco-friendly pesticide.	Kassimi et al. (2016); Park (2017)	
				Emissions trading scheme – potential exists for farmers to receive carbon credits (1 NZU = 1 tonne of sequestered CO_2) if the tree crown canopy is > 30.0% in each hectare.	Ministry for Primary Industries (2020)	
Site suitability (ecological range, hardiness, pests/diseases)	Exotic to hill country, although poplar in certain conditions can have a high survival rate when established in hill country.	Marden and Phillips (2013)	Yes – an understanding of the survival rates of poplar poles on the steepest, most erosion prone, hill country slopes would be helpful.	Native to hill country and already grows readily throughout hill country.	Spiekermann et al. (2021)	Yes - quantitative data is lacking on the age to which kānuka grow at 20 – 200 tree ha^{-1} densities in hill country, establishment
	For 300 hill country poplar poles deaths after 45 months, site factors (site conditions, socketing etc.) contributed to 28% of deaths, and	Marden and Phillips (2013)		Kānuka is reported to potentially grow up to at least 160 years and possibly as old as 300–400 years. Kānuka can grow in unfertile and moisture limited areas of hill country.	Boffa Miskell Limited (2017)	

Tree attribute	**Poplar (*Populus* spp.) attribute**		**Priority research area**	**Kānuka (*Kunzea* spp.) attribute**		**Priority research area**
	animal damage contributed to 12% of deaths.			Kānuka are susceptible to myrtle rust as they are in the myrtle family, Myrtaceae.	Boffa Miskell Limited (2017)	survival rates and the system's susceptible to myrtle rust.
	After 6 years, survivability on six hill country farms ranged from 0% to 80% (slopes varied from 0% to 32% in the study). Although the reasons for death were not quantitively measured by the authors, reasons given include animal damage, poor planting, continued erosion, winter weather fronts and poor local site conditions.	McIvor et al. (2011)		Data on the survival percentages of kānuka in varying soil conditions is required, as well as how susceptible a kānuka silvopastoral system would be to myrtle rust.		
	Leaf fungus can be an issue, with more resistant clones the main mitigation strategy.	Charlton et al. (2007)				
	As branch breaking is common due to high winds in hill country,					

Tree attribute	Poplar (*Populus* spp.) attribute		Priority research area	Kānuka (*Kunzea* spp.) attribute	Priority research area
	and fungus can be an issue, best management practice suggests felling and replanting the trees after 40 years. An understanding of the survival rate of poplars on different slope classes (especially the steepest hill country slopes) and in different environmental conditions would be informative, as well as more detailed quantitative information on the reasons for the low survival rates.				
Establishment method (seedling, cutting, pole)	Can be established as unrooted 1–3 m poles or stakes (0.5 m cuttings) which are sharpened and rammed into the ground. Sheep and small cattle can be grazed immediately. Large cattle can knock over and break poplar poles,	Marden and Phillips (2013); Phillips et al. (2014)	Yes - understanding the establishment of different planting material	With current planting technology and knowledge kānuka would need to be planted as seedlings and protected from animal browsing. Large cattle may require exclusion depending on the protection method.	Yes – little is known on the establishment of kānuka in hill country.

Tree attribute	Poplar (*Populus* spp.) attribute		Priority research area	Kānuka (*Kunzea* spp.) attribute		Priority research area
	so exclusion until the poles have established is recommended. Regular poplar poles that are planted in hill country normally take 2–3 years to produce, depending on the region, occupy a lot of land in their production and demand for them regularly outstrips supply. Understanding the establishment methods and survival rates of quicker to produce planting material (younger unrooted material or rooted material) that can be grown in a smaller amount of land with less water and lower costs would be helpful.	Ian McIvor (personal communicata-on, 26th October 2021)	(younger unrooted material or rooted material) would be helpful.	Protection with current technology would need to be strong 1.7 m plastic netting or a wire cage, supported by 2 Y posts for cattle, or by a Y post and a fibreglass rod for sheep. It is unknown at what age seedling protection can be removed.		

Tree attribute	Poplar (*Populus* spp.) attribute	Priority research area	Kānuka (*Kunzea* spp.) attribute	Priority research area
Special qualities (e.g. nitrogen fixation, thorniness, bitter leaves)	No special qualities of note.	No	A key difficulty when establishing trees in hill country is livestock browsing or damaging the tree. Livestock exclusion from paddocks is often not possible. Some land managers state kānuka leaves are bitter, which may reduce or stop browsing by sheep and cattle during establishment. Evidence for this is kānuka is already found growing readily in many parts of unproductive hill country in the presence of animals. Fresh shoots or young seedlings from commercial nurseries are likely to be browsed.	Yes – more information on the relationship between kānuka leaves and livestock is required.

Table 2.3. Silvopastoral outcomes for poplar (*Populus* spp.) and kānuka (*Kunzea* spp.) in a New Zealand hill country silvopastoral system. Tree outcomes have been adapted from von Carlowitz (1986) and Wood (1990).

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
Influence of the tree on the pasture and soil	*Evidence against* Pasture reduction beneath the canopy between 12% and 65% for poplar greater than 15 years old.	Benavides et al. (2009)	No – there is a good understanding of how poplar influences the pasture and soil.	*No evidence* *Likely outcome* Kānuka are evergreen, so this may have varying influences on the system when compared to poplar in terms of livestock nutrient transfer in winter, winter temperatures beneath the canopy of the tree and litterfall. Kānuka do not fix nitrogen.	Yes
	A relationship has been found between increased canopy closure and decreased pasture production.	Wall et al. (2006)			
	Leaf smother has been shown to depress autumn grass growth beneath poplar canopies.	Douglas et al. (2006); Kemp et al. (2018)			
	Poplars do not fix nitrogen.				
	One study found 33% less soil moisture beneath poplars when compared with open pasture in summer and autumn.	Douglas et al. (2001)			

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
	Another study found slightly more water in the top 15 cm in pasture away from poplar throughout the year, with the difference most pronounced in summer and autumn.	Guevara-Escobar et al. (2007)			
	Found no evidence that poplar facilitate the build-up of organic matter, N, P or sulphate beneath their canopies between 0 and 7.5 cm at three sites with poplar trees > 28 years old.	Guevara-Escobar et al. (2002)			
	Found varied results of soil organic matter, P and sulphate beneath fully developed poplar canopies between 0 and 15 cm compared to open pasture at two sites.	Wall (2006)			

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
	There is evidence that poplar increase exchangeable cations (calcium, potassium, magnesium, sodium) beneath their canopies, most likely because of the chemical composition of their leaves. Along with light interception and autumn pasture smother, the water use of poplar could be contributing to the reduced pasture production beneath their canopies.	Guevara-Escobar et al. (2002); Wall (2006)			
Livestock shelter	*No evidence* *Likely outcome* Trees will most likely provide less shelter to animals in winter than summer (poplars are deciduous).		Yes	*No evidence* *Likely outcome* As kānuka are evergreen it is expected the trees will provide good shade and shelter to animals in summer and winter.	Yes

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
	The summer shelter will most likely be positive for animal grazing time in summer.			The summer and winter shelter will most likely be positive for animal grazing throughout the year.		
Water and nutrient gains or losses	*No evidence* Surface runoff and nutrient loss has not been studied for poplar growing at 20–200 tree ha^{-1} densities in hill country.		Yes	*No evidence* It is unknown how kānuka impacts these system dynamics.		Yes
Biodiversity interactions (excluding livestock and the forage crop)	*Evidence against* Poplar were found to either reduce or maintain earthworm populations compared to equivalent open pasture positions. The three most abundant earthworms found beneath poplars were all exotic	Guevara-Escobar et al. (2002)	Yes	*Evidence for* 16 native and exotic bird species documented in high density (no density was given but the canopy was stated to be dense) native forest stands of kānuka.	Williams and Karl (2002)	Yes

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
	(*Aporrectodea caliginosa*, *A. longa* and *Lumbricus rubellus*). *No evidence* As far as we are aware, nothing is known on how poplar influence bird, insect and fungi populations. *Likely outcome* Biodiversity value to native fauna is predicted to be small as poplar are exotic. As poplar are deciduous, predicted to have less value to biodiversity than an evergreen tree.			Higher density forest stands host diverse invertebrate populations. *No evidence* As far as we are aware, nothing is known about how kānuka influences fungi, bird or insect populations in a silvopastoral system. *Likely outcome* Although only dense kānuka stands have been studied, a kānuka silvopastoral system is predicted to have a high biodiversity value to native fauna as the genus is native.	Boffa Miskell Limited (2017)	
Greenhouse gas implications	*Evidence for* The above and below ground carbon pool of a poplar	Guevara-Escobar et al. (2002)	Yes	*No evidence* It is unknown how kānuka impacts soil conditions and the carbon		Yes

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
	silvopastoral system was estimated to be 18.1 tonnes ha^{-1}. Nevertheless, the amount of carbon sequestered (above ground biomass) would reduce after the tree is felled.			pool of a kānuka silvopastoral system has not been estimated. Is unknown how a kānuka silvopastoral system may influence methane and nitrous oxide emissions.		
	Evidence against No clear evidence poplars increase soil organic matter beneath their canopies.	Guevara-Escobar et al. (2002); Wall (2006)		*Likely outcome* If kānuka can grow for > 100 years in hill country, it would be a long-term carbon sink in terms of above and below ground biomass when compared to hill country without trees.		
	No evidence It is unknown how a poplar silvopastoral system may influence methane and nitrous oxide emissions.					
Soil conservation effectiveness	*Evidence for* Highly effective as soil conservation trees due to their large total root length, lateral root	Hawley and Dymond (1988); Douglas et al.	No – the soil conservation effectiveness of	*Evidence for* Even though root systems of 20–200 trees ha^{-1} have not been studied, one study found kānuka	Spiekermann et al. (2021)	Yes

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
	spread (even when not fully-grown), as well as their high root tensile strength.	(2013); McIvor (2015)	poplar is well understood.	to have an average maximum effective distance of 17 m for landslide mitigation.		
	One study found poplar to have an average maximum effective distance of 20 m for landslide mitigation.	Spiekermann et al. (2021)		More research is required on the root distribution of kānuka growing at low densities (20–200 tree ha^{-1}) to gain a better understanding of the soil conservation value of a kānuka silvopastoral system.		
Time until the provision of a silvopastoral outcome	*Evidence for* Quick as poplar are fast growing.	McIvor et al. (2008)	No	*No evidence* There is no quantitative information on the growth rate of kānuka or kānuka roots growing at low densities (20 – 200 trees ha^{-1}). *Likely outcome* Slower than poplar, as poplar are a fast-growing tree, and one qualitative study provides	Boffa Miskell Limited (2017)	Yes

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
				evidence that kānuka grows more slowly than poplar.	
The ability of farmers to receive extra income streams from tree plantings	*Evidence for* Fodder – feeding poplar fodder to livestock is a practice undertaken by some farmers in summer drought conditions. Emissions trading scheme – poplars at 30% canopy are eligible for carbon credits. *Evidence against* Wood – although poplars can be pruned and harvested for timber, as of 2021, this isn't a regular practice in New Zealand.	 Charlton et al. (2007); Kemp et al. (2018)	No	*Evidence for* Emissions trading scheme – kānuka at 30% canopy are eligible for carbon credits. *No evidence* Timber – the commercial value of kānuka wood (for firewood and timber) is unknown. It is suggested that harvesting kānuka for timber is not a suitable practice for a kānuka hill country silvopastoral system because the tree density will be low (< 200 trees ha^{-1}) compared to a typical plantation density, plus when the trees are felled this would stop each tree's impact on other silvopastoral outcomes.	Yes – more information on the commercial potential of kānuka wood, honey and essential oil production is required.

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
				Honey – high density stands of trees > 40 ha are generally required to harvest high purity kānuka honey so it is unknown if honey can be harvested from a low density (20–200 trees ha^{-1}) kānuka silvopastoral system. Further research is required. Essential oil – it is unlikely that a kānuka silvopastoral system would provide enough foliage for essential oil production because of the low density (20–200 trees ha^{-1}), although further research is required to confirm this.	Boffa Miskell Limited (2017)	
Ease of pruning, management and	*Evidence against* Tall height and multi-branching habit mean management is difficult and often dangerous.	Charlton et al. (2007)	No – there are other outcomes which have a higher priority.	*No evidence* *Likely outcome*		No – there are other outcomes which have a higher priority.

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
harvesting tree products				The smaller and compact habit of kānuka compared to poplar suggests management would be easier.		
Cultural values	*No evidence* As far as we are aware, there has been no research on the cultural value of poplar, despite there being a lot of research on the functional value of poplar. *Likely outcome* Poplar is an exotic genus so it is predicted to have less value than a native genus.		Yes	*Evidence for* Kānuka is a native and so has cultural significance. Nevertheless, more work is required to understand the cultural significance of kānuka compared to other genera (native or exotic) in New Zealand.		Yes
Aesthetics	*Evidence against* One study has shown that when people are informed that shelterbelts are exotic, they are preferred less than native shelterbelts.	Brown et al. (2012)	No – despite little research, there are more important research priorities for poplar.	*Evidence for* One study has shown that when people are informed that shelterbelts contain native trees, they are preferred over exotic shelterbelts.	Brown et al. (2012)	No – despite little research, there are more important research priorities for kānuka.

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome		Priority research area
	No evidence As far as we are aware, there have been no studies on how the preference of poplar compares to other genera.			*No evidence* As far as we are aware, there have been no studies on the visual qualities of specific trees within a native tree category, or on kānuka specifically.		
Longevity of the trees	*Evidence against* Tall height and multi-branching habit mean they are not very resistant against wind damage. Best management practice suggests felling and replanting trees after 40 years (due to the impact of wind on branches and leaf fungus). Above ground silvopastoral benefits are lost when the trees are felled.	Charlton et al. (2007)	Yes – an understanding of the resistance of new cultivars to wind damage is important.	*No evidence* *Likely outcome* The small and compact habit of kānuka compared to poplar, that they are native to windy hill country conditions, and are already found on many parts of hill country, suggests kānuka are highly resistant against wind damage. If kānuka can grow up to 400 years in hill country, even if only over	Boffa Miskell Limited (2017)	Yes – confirming the longevity of kānuka is important.

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
	It is unknown how resistant new straighter cultivars are against wind as they have only recently been planted.			100 years, this means silvopastoral benefits will be lasting compared to poplar.	
Costs and ease of establishment	*Evidence for* Planting as unrooted poles is an efficient way of planting trees. Recommended practice is excluding large cattle for 2 years, but sheep can still be grazed. Survival rate is normally high for poplar. Costs $20–25 NZD to plant a pole as of 2021 (not including labour and transport costs). *Evidence against* The survival of poplar can be low, and more detailed quantitative	Marden and Phillips (2013) McIvor (2011)	Yes – more research is required on the establishment of poplar on steeper, more erosion prone slopes.	*Evidence against* The time required to plant seedlings and protect them is longer than when planting poplar poles. Cost of planting and protecting a commercially bought 50 cm kānuka seedling with protection is $20–30 NZD as of 2021 (not including labour and transport costs). *No evidence* Nevertheless, there is limited understanding into the methods of establishing kānuka in hill	Yes – comparing the establishment ease of kānuka with poplar is a priority as it is an important outcome in hill country.

Silvopastoral outcome	Poplar (*Populus* spp.) outcome		Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
	information is required to understand the instances when survival rates can be low. *No evidence* More work is required to understand the establishment of poplar on the steepest hill country slopes.			country, and more work is required to better understand kānuka establishment.	
Special qualities reducing animal interactions with the tree (thorniness, bitter leaves, etc.)	*Evidence for* Poplar can be established as unrooted poles which reduces the chance of grazing by livestock, as when leaves grow on the poles, they are normally above the reach of grazing livestock.	Marden and Phillips (2013)	No	*No evidence* *Likely outcome* If kānuka are browsed less than other genera due to their leaves being bitter, establishing the seedlings or young trees may require protection for a shorter period of time than other more desirable browse genera.	Yes – understanding the interaction between kānuka and livestock will be useful information when attempting to establish kānuka.

Silvopastoral outcome	Poplar (*Populus* spp.) outcome	Priority research area	Kānuka (*Kunzea* spp.) outcome	Priority research area
Ability to refine the tree form for improved silvopastoral outcomes	*No evidence* *Likely outcome* Even though pruning, coppicing, and pollarding is possible that will reduce management in later life, this is only done sparingly by farms.	No – there are other outcomes which have a higher priority.	*No evidence* It is unknown how a refined form will impact hill county silvopastoral outcomes, or if tree management would be taken up by landowners.	No – there are other outcomes which have a higher priority.

2.4 Key comparisons between poplar and kānuka

The following section explains in more detail the key comparative findings from the framework for important poplar and kānuka silvopastoral system outcomes.

2.4.1 The interaction of poplar and kānuka with the pasture and soil

A disadvantage of poplar is the reduced pasture growth beneath their canopies (Benavides et al., 2009). There is not conclusive evidence that poplar positively influence the water or nutrient dynamics of the agricultural system (Douglas et al., 2001; Guevara-Escobar et al., 2002, 2000; Wall, 2006). Possible attributes responsible for this competitive relationship with pasture could be their high-water use (Guevara-Escobar et al., 2000), their uncompact form discouraging preferential grazing beneath their canopies, their large canopy causing too much shading, or their deciduous nature causing grass smothering (Douglas et al., 2006; Kemp et al., 2018), potentially reducing animal nutrient transfer in winter or reducing their influence on winter temperatures beneath their canopies (Guevara-Escobar et al., 2007). Some of these factors are explored below.

Water use by fully-grown individually spaced poplar trees in hill country (37.2 stems ha^{-1}) was investigated by Guevara-Escobar et al. (2000). They found average individual tree water use was 180.1 L day^{-1} during a spring study period, which equates to an equivalent water use of 1.2 mm day^{-1}. The maximum water use was 417.0 L day^{-1}. A review of tree water use for 67 species (including hybirds) by Wullschleger et al. (1998) suggests that the average water use by poplars in the Guevara-Escobar et al. (2000) study of 180.0 L day^{-1} is high. As well as having high water use, 6-month-old *Populus euramericana* trees were shown to have isohydric behaviour in which leaf water potential was maintained in well-watered, medium deficit and severe deficit soil conditions (Tardieu and Simonneau, 1998). Therefore, if the poplar cultivars planted in New Zealand also show isohydric behaviour, even in severe deficit soil conditions, they will have the same high water use as in saturated soil conditions (Tardieu and Simonneau, 1998). The water use of kānuka is unknown, however, if kānuka uses less water than poplar, this may be beneficial in terms of reducing tree-pasture water competition in the silvopastoral system.

Poplar are deciduous and lose their leaves in autumn, reducing the ability of the tree canopy to buffer air temperatures during winter months, influencing pasture growth and animal shelter effects. This was confirmed by Guevara-Escobar et al. (2002) who did not find evidence that poplar buffer winter temperatures. Kānuka trees, however, are evergreen, and maintain their foliage year-round. Previous research presents examples of trees in agroforestry systems buffering winter air temperatures beneath their canopies. In central-western Spain, Moreno et al. (2005) found the daily minimum air temperature to decrease from 7.4 °C 1 m from the trunk to 6.3 °C 20 m from the trunk in the *dehesa* system in Spain. In a *Paulownia* spp. silvo-arable system in eastern-central China, mean winter air temperature was 0.2–1.0 °C higher under trees compared with open cropping land (Chang et al., 2018). Based on these findings, we postulate that having an evergreen tree canopy over hill country pastures in winter could buffer winter air temperatures, and this may result in increased pasture growth when temperature may otherwise limit growth.

The presence of tree canopies during winter is likely to attract more animals as they seek shelter from colder temperatures and wind. As animals are a key mechanism for nutrient transfer in hill country (Saggar et al., 1990), if animals do preferentially spend time beneath kānuka in winter, this could have important implications for nutrient build-up beneath the canopy. Moreover, this should have livestock health benefits, in addition to potentially reducing live weight losses as less energy may be used maintaining body temperatures. On the contrary, a canopy during winter will reduce the amount of light reaching the ground or pasture. If light limits growth during winter months, this could negatively affect pasture growth. Additionally, if livestock spend too much time beneath winter canopies under certain trees, this may result in excess livestock camping, potentially resulting in soil compaction and grass smothering.

In agroforestry systems, trees add leaves to the soil which can help build-up soil organic matter and nitrogen (Cardinael et al., 2017; Rossetti et al., 2015). For *P. maximowiczii* Henry x *P. nigra* L. cultivars, Douglas et al. (2006) recorded 1.7 t DM ha^{-1} year^{-1} of leaf fall in low density unevenly planted poplar stands (25–400 stems ha^{-1}). Douglas et al. (2006) found open pasture to have more annual grass biomass (8.5 t DM ha^{-1}) than grass plus poplar leaf biomass under poplars (8.3 t DM ha^{-1}). The reduction in pasture growth beneath the canopies (6.6 t DM ha^{-1} year^{-1}) was not compensated by the 1.7 t DM ha^{-1} year^{-1} addition of poplar leaves. Moreover, the nutritional value of recently shed poplar leaves has not been studied and although their fodder quality is good (Charlton et al., 2007), after the leaves have begun to decompose they would most likely have a lower nutritional value when compared to green leaves on the canopy. Kānuka leaf fall has been measured in high density unmanaged mixed stands of kānuka and mānuka (no density was given, see Figure 2.3) (Lambie and Dando, 2019). The two sites in the study had an average leaf fall of 2.2 t DM ha^{-1} year^{-1}. In contrast to poplars, this leaf fall occurred throughout the year, which may potentially reduce grass smothering during autumn, and as fewer leaves may be grazed by animals, increase the amount of organic matter that is recycled back into the soil.

These factors suggest kānuka could have a facilitating relationship, as opposed to poplar's competitive relationship, with the hill country pastoral environment. If kānuka is found to positively influence soil conditions beneath their canopies, this may have important implications for the productivity of low producing hill country, as well as for soil erosion and the hydrology of the system. Comparing the agricultural environment beneath poplar with genera of contrasting attributes would be informative and help disseminate which attributes may be leading to the negative interaction between poplar and pasture.

Figure 2.3. A high density mānuka-kānuka shrubland study site for the leaf fall study by Lambie and Dando (2019, p. 612). Permission has been given by the authors to reproduce this photograph.

2.4.2 Longevity

The 25 m or greater height and spreading branches of older poplar cultivars (high vulnerability to branch windbreak), and susceptibility to fungus, mean their longevity is low (~40 years) (Charlton et al., 2007), when compared to the holm oak *(Quercus ilex* L.*)* tree of the *dehesa* agroforestry system in Southern Europe (trees can grow for 100 years to 250 years) (Plieninger et al., 2003). This impacts the long-term influence of each tree and requires that trees are felled and replanted. This represents a cost to the farmer or taxpayer and reduces the long-term carbon sequestration potential of each tree. The framework presents evidence that kānuka may have a similar longevity to holm oak as 1) they can potentially grow up to 400 years old (Boffa Miskell Limited, 2017), 2) hill country is their ecological range meaning that they may be less susceptible to disease (further research is required to understand the threat from myrtle rust) and 3) their relatively shorter height will most likely result in less branch windbreak. The longevity of new poplar cultivars that have been developed to grow in a more compact form is unknown.

2.4.3 Establishment

The ability to plant poplar as 2–3 m unrooted poles is a major advantage of the system as sheep and small cattle can be grazed immediately after establishment, and planting is quick in comparison to the planting and protection of commercially bought 50 cm kānuka seedlings. This is a major advantage of poplar, although if kānuka was adopted as a silvopastoral tree, planting technology would most likely improve with increased demand. The cost of planting and protecting 50 cm kānuka seedlings is comparable to poplar pole establishment (not including labour and transport costs).

2.4.4 Time until an influence on the agricultural environment and soil conservation

Another advantage of establishing poplar poles is they are already 1.5–2.5 m high when they are planted. This, in addition to their quick growth rate (McIvor et al., 2011; Wilkinson, 1999), means that the time until they have an influence on the silvopastoral environment (above and below ground) is quick when compared to establishing kānuka seedlings. This quick growth rate in conjunction with their expansive root system means poplar are highly effective soil conservation trees (Douglas et al., 2013; Hawley and Dymond, 1988; McIvor et al., 2015). Despite no research on the root systems of kānuka trees growing at a spacing of 20–200 trees ha^{-1}, tree influence modelling has shown kānuka to have an average maximum effective distance of 17 m, compared to 20 m for poplar (Spiekermann et al., 2021). This provides some evidence kānuka may be an effective soil conservation tree, as is the case for poplar.

2.4.5 Cultural values

Kānuka is a native to New Zealand and as such has cultural significance. Kānuka presents an opportunity as a hill country silvopastoral tree that can potentially provide many beneficial utilisation outcomes alongside its cultural significance.

2.4.6 Bird biodiversity

To the best of our knowledge, bird populations within poplar silvopastures have not been studied in New Zealand. This is also true of kānuka in pastured hill country, despite research showing the benefits to biodiversity of other global silvopastoral systems (McAdam and McEvoy, 2009; Peri et al., 2016b).

Agricultural landscapes in New Zealand hold great potential to harbour high diversity (Blackwell et al., 2005; MacLeod et al., 2012, 2008). Blackwell et al. (2005) found 'conventional' sheep and beef farms had significantly greater species abundance (total number of birds recorded) and diversity (number of different species) than all other studied landscape types - native forest, scrub, pine plantations and kiwi-fruit orchards. However, there were 2–3 times fewer native species on the sheep and beef farms and kiwi-fruit orchards compared with native forest, pine plantations and scrub. A similar conclusion was found for arable land in the South Island of New Zealand: species diversity was similar for native (16) and introduced (17) birds over a 2-year study, although species richness was much higher for introduced bird species (winter: 9.33 ± 0.35; breeding season: 11.2 ± 0.36) than for native species (winter: 3.31 ± 0.23; breeding season: 1.74 ± 0.23) (MacLeod et al., 2012).

Although native bird populations have been shown to be smaller in productive landscapes, Blackwell et al. (2005) found bird richness variation within sheep and beef farms. The number of native birds increased on farms which had more woody vegetation. Blackwell et al. (2005, p. 70) conclude that there is great potential for "production landscapes to be flush with biodiversity" if there is more woody vegetation growing on New Zealand productive landscapes.

Williams and Karl (2002) reported that a dense canopy of kānuka supported 15 bird species, with korimako/bellbird (*Anthornis melanura*), pīpipi/brown creepers (*Mohoua novaeseelandiae*) and riroriro/grey warbler (*Gerygone igata*) being most common in the kānuka stands compared to gorse stands. This study gives some evidence that the native and evergreen nature of kānuka may present an opportunity for enhancing the connectivity of New Zealand's forested ecosystems within agricultural landscapes.

2.4.7 Additional income

Honey from mānuka has been medically popularised because of its non-peroxide anti-bacterial properties (Allen et al., 1991; Brooks et al., 2016). Kānuka also has anti-bacterial properties and can be used as an antiseptic on wounds (Lu et al., 2013). In addition, kānuka honey has been shown to have anti-viral (Bloor, 1992), immunostimulatory (Gannabathula et al., 2012) and anti-inflammatory properties (Tomblin et al., 2014).

To produce un-diluted honey which maximises these beneficial properties, bees must harvest as much nectar as possible from the flower of interest. Mānuka is currently commercially produced at a large scale in New Zealand, requiring monocultures of mānuka greater than 40 ha to achieve desired honey quality (Boffa Miskell Limited, 2017). If kānuka was growing singly spaced within a pasture system, there is a high chance other flowers would be available to foraging bees, such as clover (*Trifolium* spp.) or gorse, diluting the quality of honey produced. Boffa Miskell Limited (2017, p. 19) does states that some interviewed farmers suggested grazing adjacent pastures very low during the flowering season to reduce nectar dilution, although "there are no data to verify the effectiveness of this strategy".

Essential oil can be produced from kānuka leaves. Recent research has explored the use of this essential oil as an eco-friendly pesticide for aphid populations (Kassimi et al., 2016) and *Drosophila suzukii* (Park et al., 2017) with encouraging results. Leaves and branches under 10 mm in diameter are harvested every 3 years to 5 years from trees up to 7 years old, as these trees have the greatest leaf:shoot ratio and the tree height ensures ease of harvest (Essien et al., 2019). It is unlikely that a kānuka silvopastoral system with a 20 trees ha^{-1} to 200 trees ha^{-1} density would provide enough foliage for economic essential oil production.

Landowners can earn credits for sequestering carbon (1 New Zealand Unit (NZU) = 1 tonne of sequestered CO_2) from the atmosphere through planting trees (Ministry for Primary Industries, 2020). These NZUs can be traded based on a market-driven unit price. Although research is required to confirm this, it is likely that kānuka and poplar planted at 20 trees ha^{-1} to 200 trees ha^{-1} would cover the 30% land area threshold required for farmers to be able to receive NZUs. As the NZU price increased by over 1000% from 2013 to 2020 (Carbonnews, 2020; Theecanmole, 2016), this could become a valuable revenue opportunity for farmers who wish to maintain their land in pastoral farming.

2.5 Evaluation of the framework

A major benefit of this new framework is that it considers visible and known tree attributes so the potential benefits and costs of a particular genera can be assessed before research is undertaken. This is important in the case of kānuka, as it has received little research in a silvopastoral context to date, even though the framework provides evidence that kānuka has many benefits in certain outcomes when compared to poplar. This provides the means to 'screen' genera quickly before undertaking resource-intensive research. Moreover, it clearly highlights the tree attribute differences which may be causing alternate silvopastoral outcomes. Trees can then be more rigorously compared and selected based on these attributes.

As tree genera differ in their attributes and outcomes, it is apparent each genus will have distinct advantages and disadvantages. Viewing silvopastoral trees as a set of attributes and subsequent outcomes clearly shows them as 'a set of *trade-offs* rather than a real *solution*' (Sowell, 1987, p. 14, emphasis in original). Kānuka will not be a panacea species, nor will any other. Nevertheless, by presenting species using this novel framework, with their advantages and disadvantages clearly conveyed, this will result in more informed silvopastoral research directions.

Species and cultivars within genera will have different attributes also, as outlined in a poplar and willow planting guide (Charlton et al., 2007). This will most likely be the case for the seven viable species of kānuka. Nevertheless, this was a level of detail beyond the scope of this review, although the framework could be used for within-species comparisons.

A given tree's outcome may vary with differing growing situations, such as pastoral livestock type, field-scale paddock variations or climate. The framework could also be used to compare the same species or genera in these differing environments.

One limitation of the framework being used as it is in this paper is the limited space within the tables. Using a table format does not present itself well to a more descriptive comparison between species for outcomes where little information is known. This was rectified in this paper by having a more descriptive comparison section below the tables. One solution to this would be to put the framework into a database, which could clearly show evidence for and against an outcome, and provide an opportunity for more descriptive information in a notes section of the database.

Additionally, using the framework in a table format would be difficult when more than two species or genera were assessed, as the tables would most likely become cluttered with the information. Using the framework in a database would be very beneficial if more than two species or genera are compared.

When comparing the two genera, it would be helpful to add a common unit account for each of the outcomes so they can be quantitatively compared. Nevertheless, as stated in the introduction, this was beyond the scope of this review and the use of the framework in this paper is to review poplar and kānuka as silvopastoral trees and inform future research directions, not to provide a tool for quantitively evaluating tree planting decisions. This would be a valuable use of the framework, however, if enough information was available for specific species or genera.

Some of the outcomes could have had sub-categories, especially for ‘above ground tree habit and phenology’. We decided not to use sub-categories because only this first outcome really warrants them, and we felt it was important to keep all the outcomes consistent. Moreover, the potential sub-categories such as ‘impact of the silvopastoral tree on pasture’, ‘impact of the silvopastoral tree on the soil’ and ‘impact of the silvopastoral tree on water’ are very much interlinked, as the soil is related to the availability of water, and both the soil properties and the availability of water are related to pasture growth. By maintaining one larger group, this allows for a summary statement at the end of each category, and makes it clear the holistic nature of this outcome.

Finally, as is the case in systems, many of the outcomes themselves interact with each other. For instance, ‘the time until the provision of a silvopastoral outcome’ interacts with ‘the influence of the tree on the pasture and soil’, ‘livestock shelter’ and ‘soil conservation effectiveness’, and ‘the influence of the tree on the pasture and soil’ interacts with ‘water sediment and nutrient gains and losses’. Nevertheless, outcome-outcome interactions were not included in the framework as the focus of the framework is how the tree attributes relate to silvopastoral outcomes. We think research prioritisation and tree selection for researchers and land managers will be guided specifically by the presentation of the outcomes and their interactions with tree attributes.

2.6 Conclusion

Silvopastoralism is a land management tool which can offer holistic opportunities to improve degraded agricultural landscapes. In order that silvopastoral systems are researched, assessed and compared in a holistic manner, a framework that outlines all their known silvopastoral outcomes is required. Moreover, by relating bio-physical tree attributes to these silvopastoral outcomes, tree selection for research and planting can be optimised based on a system's outcome needs.

The framework gives emphasis to the plethora of beneficial influences of trees to silvopastoral systems that are often not considered by New Zealand land managers, such as shelter provision, longevity, extra income from trees, the benefits of a winter tree canopy, the system's hydrology, and habitats for local fauna populations. This process clearly conveys the complexity of silvopastoral systems and extends the focus beyond more commonly researched outcomes (pasture production and soil conservation in the case of hill country).

The framework was then used to review specific silvopastoral systems, highlighting research gaps and generating research priorities. In a New Zealand hill country case study, this paper shows the potential value of kānuka as a silvopastoral genus, a tree with a very different set of tree attributes to poplar, the most commonly planted silvopastoral tree in hill country. Kānuka may have improved outcomes in terms of pasture production, longevity, biodiversity value, shelter and ease of management due to its smaller size, evergreen nature and that it is native to hill country. Nevertheless, more research is required on kānuka to better understand these benefits and inform its use.

There remain many outcome knowledge gaps for poplar used in a low density (20–200 trees ha^{-1}) silvopastoral system such as biodiversity interactions, livestock shelter, greenhouse gas implications and water and nutrient gains or losses. This is surprising due to the amount of research that has been done on poplar and its widespread use. If poplar are to be fully evaluated and more fairly compared with other genera, researching these other silvopastoral outcomes is essential.

Chapter 2 summary

This chapter presented a literature review in an alternative form, which created a novel framework that linked silvopastoral tree bio-physical attributes to silvopastoral outcomes. The paper then reviewed and compared poplar, the most commonly planted silvopastoral tree in New Zealand hill country, and kānuka, as silvopastoral trees within the framework. The review indicated that there are many outcome knowledge gaps for poplar used in a low density (20–200 trees ha^{-1}) silvopastoral system such as biodiversity interactions, livestock shelter, greenhouse gas implications and water and nutrient gains or losses, and highlighted the potential value of kānuka as a silvopastoral genus because of its smaller size, evergreen nature and that it is native to hill country. Nevertheless, more research is required on kānuka to better understand these benefits and inform its use.

Chapter 3 A fresh approach to silvopastoralism in New Zealand with kānuka

This chapter explores hypothesis 1 and measures how kānuka impacts pasture production, and discriminates which variables contribute to pasture production differences under and away from the trees.

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3.1 Introduction

In many situations, 'tree-pasture' silvopastoral trees can become 'islands of fertility' (Gallardo, 2003; Marañón et al., 2009; Rossetti et al., 2015), build soil organic matter (Howlett et al., 2011; Moreno Marcos et al., 2007; Rossetti et al., 2015), conserve soil moisture (Joffre and Rambal, 1988; Peri, 2005) and improve soil structure (Belsky et al., 1993; Fernández-Moya et al., 2011). Moreover, silvopastoral systems can be carbon sinks in terms of above and below ground biomass and potential increases to soil carbon (Aryal et al., 2019; Seddaiu et al., 2018), improve the local agricultural microclimate (Bahamonde et al., 2009; Moreno Marcos et al., 2007), provide shelter and shade to livestock (Betteridge et al., 2012; Blackshaw and Blackshaw, 1994; Soares et al., 2009) and provide habitat to local bird populations (McAdam and McEvoy, 2009; Pulido and Díaz, 1992; Rodríguez-Rojo et al., 2022).

One region that could benefit from wider use of silvopastoralism is New Zealand hill country, which is an agricultural area in New Zealand that is defined as steep or hilly land (> 15°), having an altitude < 1000 m asl and pastoral farming as its main land use (sheep, cattle and deer) (Dodd et al., 2016). Silvopastoralism is already used in New Zealand hill country to mitigate soil erosion (Basher, 2013; Douglas et al., 2013; McIvor et al., 2015; Wilkinson, 1999). The most commonly planted and researched silvopastoral genus is poplar (*Populus* spp.) (Benavides et al., 2009; Hicks and Anthony, 2001; Kemp et al., 2018; Wilkinson, 1999). Poplar have been selected because of their quick growth (Marden and Phillips, 2013; McIvor et al., 2011), large root system (McIvor et al., 2015, 2008; Phillips et al., 2014), high evapotranspiration rates when growing (Guevara-Escobar et al., 2000; Wilkinson, 1999; Wullschleger et al., 1998) and ability to plant the trees as unrooted sharpened coppiced poles in the presence of grazing sheep and cattle (Phillips et al., 2014). Nevertheless, past published studies only report negative impacts to pasture production (Benavides et al., 2009), with reductions ranging from 12% to 65% compared to open pasture

(Benavides et al., 2009; Devkota et al., 1997; Douglas et al., 2001; Gilchrist et al., 1993; Guevara-Escobar et al., 2007; Wall, 2006).

There are, however, many examples of research reporting increased pasture production under silvopastoral trees in other systems (e.g. Callaway et al., 1991; Frost and McDougald, 1989; Moreno, 2008). In three Spanish *dehesa* silvopastoral sites with annual rainfall ranging from 452 mm to 661 mm, mean pasture production increased by 19% under holm oak (*Quercus ilex* L.) compared to open pasture (Moreno, 2008). Frost and McDougald (1989) found on average 63% and 50% more pasture production under the canopy of blue (*Q. douglasii* Hook. & Arn.) and interior live (*Q. wislizeni* A. DC.) oak compared to open pasture, respectively, at sites with an average rainfall of 487 mm. This effect has also been shown in the ñire (*Nothofagus antarctica* (G. Forst.) Oerst.) forests of southern Patagonia, Argentina, with ~700 mm annual rainfall, with maximum pasture production being achieved at a 50–60% canopy cover compared to open pasture in a severely water stressed site (Peri, 2005).

The tree attributes of poplar contrast with the southern European and Californian oak silvopastoral systems, and the ñire forests of southern Patagonia. For instance, these other silvopastoral trees not in New Zealand most likely grow slower than poplar (although a trial of all these trees in the same conditions has not been done) (Kolb, 1990; Peri et al., 2016a; Phillips et al., 2014; Stockley, 1974; Wilkinson, 1999), and so use less water and nutrients during establishment (Binkley, 2012). Moreover, the height of the main trees used in southern Europe (*Q. ilex* and *Q. suber* L.) and in Patagonia (*N. antarctica*) is between 4 m and 15 m (Gouveia and Freitas, 2008; Peri et al., 2016a; Pulido et al., 2001; Sánchez-González et al., 2005), and those in California (*Q. douglasii* and *Q. wislizeni*) are typically between 7 m and 20 m in height (Roig et al., 2013). This compares to poplar that are > 30 m (Mackay-Smith et al., 2021), and is important for pasture production because larger trees have been show to use more water (Binkley, 2012; Binkley et al., 2002; Otto et al., 2014).

Furthermore, the systems in southern Europe, California and southern Patagonia use native trees (Peri et al., 2016a; Plieninger et al., 2003; Ratliff et al., 1991), which is most likely why the trees in the *dehesa* system in Spain can live up to 250 years (Plieninger et al., 2003), and those in the ñire forests of Patagonia can live up to at least 180 years (Peri et al., 2016a). This compares to poplar which often experience wind damage and leaf rust, and the recommended management practice is to fell and replant the trees after 40 years (Charlton et al., 2007). These reasons suggest that it is likely that the systems in southern Europe, California and southern Patagonia have a better chance of positively impacting soil resources and pasture production because of reduced tree competition over an extended period, compared to genus that requires felling and replanting after 40 years.

A fresh approach is needed in New Zealand that uses trees with similar attributes to these other silvopastoral systems to form intergenerational systems that have a better chance of increasing pasture production compared to open pasture, thus forming multifunctional landscapes. Kānuka (*Kunzea* spp.) is a native genus that has 10 endemic species in New Zealand (de Lange, 2014). Many of these species are trees that are naturally common in New Zealand hill country (Bergin et al., 1993; de Lange, 2014; Spiekermann et al., 2021), which have similar attributes to *Nothofagus antarctica* and the oaks mentioned above.

For instance, kānuka grow slower (Boffa Miskell Limited, 2017; McIvor et al., 2011; Phillips et al., 2014; Stockley, 1974) and are smaller (8–20 m high) (Mackay-Smith et al., 2021) than poplar, so most likely compete less for soil resources (Binkley, 2012; Binkley et al., 2002; Otto et al., 2014). Moreover, kānuka is a native to hill country and is reported to grow for at least 300 years (Boffa Miskell Limited, 2017). These similarities between kānuka and other native silvopastoral trees globally leads to the hypothesis that kānuka will increase the availability of water and nutrients for pasture growth because of reduced competition and compounded positive influence on the local pastoral environment, increasing pasture production under kānuka canopies compared to open pasture.

Kānuka has never been studied in terms of its impact on pasture production. If kānuka increases pasture production under its canopy, this may not only be transformative for New Zealand pastoral farming, but it will provide evidence as to whether there are universal tree attributes responsible for positive pastoral outcomes in silvopastoral systems. If these can be found, this will greatly help the creation, design and management of future silvopastoral systems. The objectives of this study are to 1) measure the impact of kānuka on pasture production when compared to equivalent open pasture positions, and 2) identify and discriminate the variables that contribute to pasture production differences between tree and open pasture positions.

3.2 Methods

3.2.1 Study areas

This study was undertaken at two sites in the North Island of New Zealand. The first was in the Wairarapa region, ~10 km north of Martinborough (Wairarapa site), and the second was in the Hawkes Bay region, ~20 km south of Waipukurau (Hawkes Bay site) (Table 3.1; Figure 3.1). Two sites with similar environmental and soil conditions were selected to increase the reliability in the results (Table 3.1).

Both sites were on typical commercial sheep and beef farms with naturalised and permanent pasture. The most common pasture species in hill country are browntop (*Agrostis capillaris* L.) and perennial ryegrass (*Lolium perenne* L.), however, the pasture species composition of hill country pastures do vary depending on environmental conditions (López et al., 2006; Nicholas, 1999). Individual *Kunzea robusta* de Lange et Toelken (kānuka) trees grew throughout the paddocks at both study sites at ~10 trees ha^{-1} to ~2000 trees ha^{-1} (Figure 3.1B; Figure 3.1C). It is likely that the trees at both sites established naturally as seedlings following land clearance for grazing.

Table 3.1. Site characteristics for the two study sites.

Study site	Wairarapa	Hawkes Bay
Location	41°08′41.3″S, 175°29′58.3″E	40°08′25.9″S, 176°23′39.1″E
Region	Wairarapa, North Island of New Zealand	Hawkes Bay, North Island of New Zealand
Elevation (m)	122	288
Basement rock	Sandstone	Mudstone
New Zealand soil classification	Mottled Argillic Pallic Soil (Hewitt, 2010)	Mottled Argillic Pallic Soil (Hewitt, 2010)
US soil classification	Ustalf (Hewitt, 2010)	Ustalf (Hewitt, 2010)
Topsoil type	Silt loam	Silt loam
Subsoil type (B horizon)	Silty clay loam	Silty clay loam
Mean 30-year annual rainfall (mm)	903 (min: 548; max: 1297) Station 2631, 6.6 km from the site, elevation: 61 m (CliFlo, 2021)	883 (min: 527; max: 1483) Station 2523, 5.8 km from the site, elevation: 153 m (CliFlo, 2021)
Mean 10-year annual temperature (°C)	18.3 (min: 17.5; max: 19.0) Station 21938, 15.0 km from the site, elevation: 22 m (CliFlo, 2021)	16.7 (min: 15.8; max: 17.5) Station 25820, 15.3 km from the site, elevation: 341 m (CliFlo, 2021)
Paddock topography	Moderately to severely steep (15–40°)	Rolling to moderately steep (10–35°)
Livestock operation	Sheep and beef	Sheep and beef
Aspect	NE	NW
Measurement position slope gradient	20–25°	20–25°

At the Wairarapa site, livestock was rotationally grazed for 2 days to 3 days at a time throughout the year with a grazing intensity of 40 lambs ha^{-1} day^{-1}, 57 ewes ha^{-1} day^{-1}, 9.1 Angus cows ha^{-1} day^{-1} and 3.4 Friesian bulls ha^{-1} day^{-1}. At the Hawkes Bay site, pregnant ewes during lambing were set stocked for about 1 month in spring and summer at a stocking rate of 5.7 ewes ha^{-1}. The paddock was also rotationally grazed by Angus cows for one week at a time throughout the year at 0.8 cows ha^{-1} day^{-1}. Fertilisers that contained 21.5 kg P ha^{-1} and 37 kg S ha^{-1} were annually surface applied at the Wairarapa site in early summer. The annual fertilisation at Hawkes Bay was either 25 kg N ha^{-1} and 28.75 kg S ha^{-1}, or 25.8 kg P ha^{-1} and 42 kg S ha^{-1}, which was surface applied in winter. There were also some years at the Hawkes Bay site where no fertiliser was applied because of sufficiently high Olsen-P soil tests.

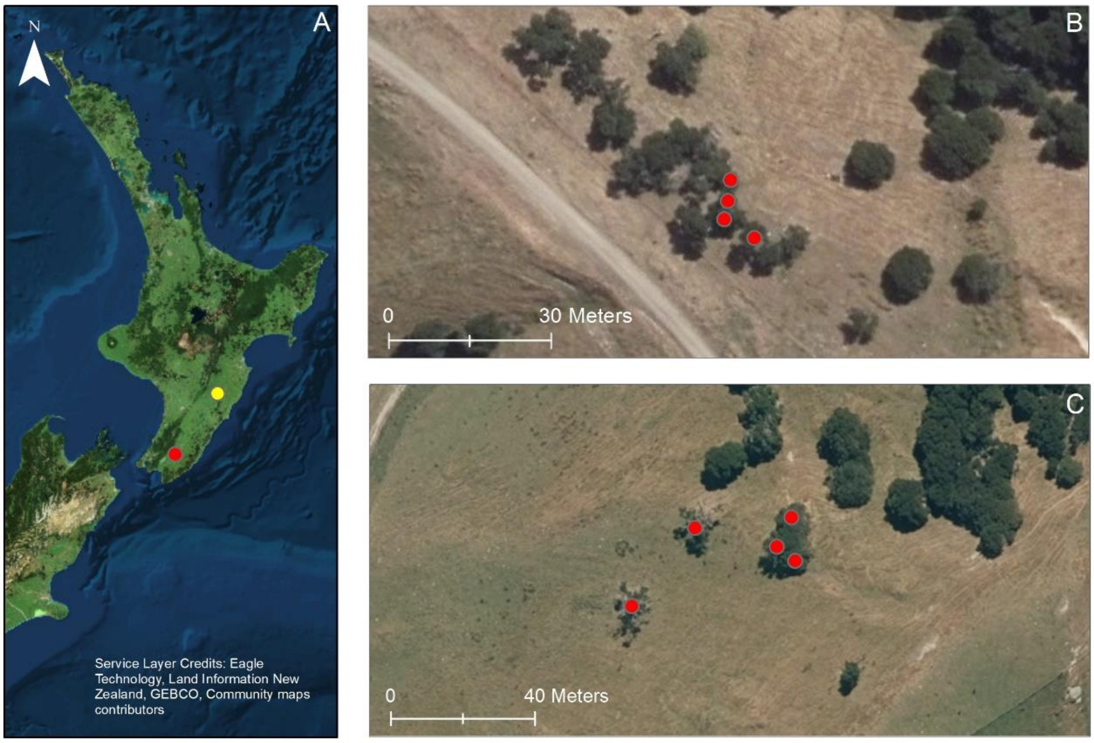

Figure 3.1. Study site locations and individual trees evaluated at each site. A: Location of the study sites in New Zealand (the red dot is the Wairarapa site and the yellow dot in the Hawkes Bay site). B: The studied kānuka trees at the Wairarapa site (red dots show the individual trees evaluated). C: The studied kānuka trees at the Hawkes Bay site (red dots show the individual trees evaluated). B and C are from the same satellite layer as A.

3.2.2 Study design and measurements

At each study site, pasture measurement positions were in pairs that represented the two treatments (kānuka pasture and open pasture). One pasture position was half-way under an individually spaced kānuka tree canopy and stem (kānuka pasture), and the other was in an equivalent pasture position (with a similar slope gradient and slope position) in open pasture at least 15 m from the nearest tree trunk (open pasture). Each open pasture position was at least 15 m from the trunk of the paired kānuka pasture position because the drip line (edge of canopy) was ~5 m from the trunk for all trees, and a distance of at least three times the drip line was selected as 'open pasture' because Howlett et al. (2011) used three times the drip line for their open pasture positions. Other authors have selected 2.5 times the drip line for open pasture positions (Fernández-Moya et al., 2011; Rossetti et al., 2015), so we selected at least three times to maximise the contrast between open and kānuka pasture positions.

There were four pasture position pairs at the Wairarapa site and five at the Hawkes Bay site. This represented nine tree replicates in total for each treatment (kānuka pasture and open pasture) (Figure 3.1B; Figure 3.1C). The height of the trees was ~10 m at Wairarapa and between 10 m and 15 m at Hawkes Bay. The exact age of the trees are unknown, but historic aerial imagery show that the trees at the Wairarapa site are over 80 years old (Retrolens, 2021). Aerial imagery could not be found for the Hawkes Bay site, however, they are most likely at least this old as the trees are larger than the ones at Wairarapa. All pasture positions were between the slope gradients 20° and 25° and were on the same hill slope.

The trees in each paddock were selected based on their being four or five individual kānuka trees and equivalent open pasture areas in close proximity to each other. Trees were selected in this way because soil moisture sensors were installed permanently into the ground that had to be connected to a central data logger, and the cable lengths were no more than 20 m long. Moreover, at both sites there were livestock camping spots under a few trees on the downslope side, and these were specifically avoided when selecting study trees.

Measurements were taken for two years from 12th December 2019 until 11th December 2021. At each position, pasture production, soil fertility, soil physical properties, soil temperature, soil moisture and light interception were quantified.

Pasture production was measured using the pre-trimmed exclusion technique (Radcliffe et al., 1968). Pasture was harvested using one pasture cage per position (n = 9 per treatment). For each cage, pasture was pre-trimmed with electric clippers to 1 cm (López et al., 2003b). The pasture was harvested to 1 cm from a 25 cm x 50 cm quadrat within the pasture cage area after a ~2-

month regrowth period (depending on the season and pasture height). Both sites were cut either on the same day or on consecutive days. After the quadrat area was sampled, the cage was moved to a new pre-trimmed pasture spot within the same position. Cages were rotated between three pasture cage spots within each position. This allowed livestock grazing and nutrient return to continue within the sampling locations throughout the study. If there were obvious dung or urine deposits where a cage was to be placed, an alternative position was used. After collection, each sample was oven-dried for 72 hours at 70 °C and weighed. Every season, a subsample was taken and split into live and dead matter groups. These subsamples were also oven-dried for 72 hours at 70 °C and weighed. This meant dead matter and green dry matter production (GDMP) (total weight minus dead matter) could be compared between treatments.

Volumetric soil moisture (VSM) was continuously measured using time domain reflectometry Campbell Scientific CS616 soil moisture sensors (sensor length 30 cm) (Campbell Scientific, USA). Sensors were installed vertically at two depths (0 cm to 30 cm and 30 cm to 60cm) in the centre of each measurement position. There was one Campbell Scientific CR1000 data logger at the Hawkes Bay site with cables extended using two Campbell Scientific 16/32B multiplexers. One Campbell Scientific CR1000 data logger and one Campbell Scientific CR800 data logger were used to collect data from the Wairarapa site. All data loggers and multiplexers were contained in waterproof electrical boxes, connected to a 12V battery that was charged by a solar panel. Data loggers took readings every 30 minutes. VSM measurements were averaged over the measurement period for each position (n = 9 per treatment), and VSM summer measurements were defined as VSM measurements between 15th December and 14th March.

Soil fertility was systematically sampled from a pasture cage spot in each position using ten soil cores (0–7.5 cm) in December 2019 and December 2021. After sampling, the cores were bulked together to form one representative sample per position. Even though a third sample was taken from the third pasture cage spot in December 2020, only the measurements in December 2019 and December 2021 were analysed because two repeated measurements was deemed sufficient for the purposes of the study. They were then sent to a testing laboratory (Hills Laboratories, Hamilton; Certified NZS/ISO/IEC 17025:2005 by International Accreditation New Zealand) where they were analysed for pH (1:2 soil to water) (Blakemore et al., 1987), Olsen-phosphorus (Olsen-P, 30 minute bicarbonate extraction followed by Molybdenum Blue Colorimetry) (Olsen et al., 1954), soil organic matter (Dumas combustion was used to calculate total carbon and organic matter was 1.72 x total carbon) (Nelson and Sommers, 1996), total-nitrogen (total-N, Dumas combustion), sulphate-sulphur (sulphate-S, 0.02M potassium phosphate extraction followed by Ion Chromatography) (Searle, 1988), sodium/potassium/magnesium/calcium (Na/K/Mg/Ca, 1M neutral ammonium acetate extraction followed by ICP-OES) (Blakemore et al., 1987) and cation exchange capacity (CEC, summation of extractable cations (K, Ca, Mg, Na) and extractable acidity) (Hesse, 1971). Both the measurements from December 2019 and December 2021 were averaged to form a single soil fertility measurement for each position (n = 9 per treatment).

Three cm (height) by 4.8 cm (diameter) soil cores were taken between 2–5 cm in the topsoil in September 2021 and used to measure bulk density, particle density, pore size distribution and the water retention curve. Four cores were sampled 50 cm to the left of the VSM sensor in each position and averaged to form one measurement per position (n = 9 per treatment). Particle density was calculated using a subsample from one replicate per position according to the method described by Gradwell and Birrell (1979), and with bulk density used to calculate porosity for the top soil (porosity 2–5 cm). For the pore size distribution and water retention curve, cores were saturated from below then equilibrated at the matric potential values of -6 kPa (hanging water column) and -1500 kPa (in a pressure chamber), which correspond to the pore sizes of < 54 μm and < 0.2 μm, respectively. Macroporosity was defined as pore sizes draining between 0 kPa (saturation) and -6 kPa (Dörner et al., 2015). Plant available water capacity was defined as water draining between -6 kPa and -1500 kPa (Dörner et al., 2015). Bulk density was also measured between 40 cm and 45 cm using 5 cm (height) by 4 cm (diameter) soil cores taken using a soil corer. Bulk density was measured at 40 cm because it was within the depth of the soil moisture sensors between 30 cm and 60 cm.

Photosynthetically active radiation (PAR) was measured 50 cm above the pasture in the centre of each position using a Skye Spectro Sensor 2 data logger attached to a Skye PAR sensor (Skye Instruments, UK). PAR was measured one day per season 30 times at solar noon, solar noon +2 hours and solar noon -2 hours on a cloudless day. Measuring over a 4-hour window captured variation in tree shading variation during the day. After each set of 30 measurements at each tree position, one measurement was taken in the paired open pasture position. Light interception (LI) by the kānuka trees was calculated by subtracting each kānuka pasture PAR measurement from the paired open pasture PAR measurement. One LI measurement was formed per kānuka pasture position by averaging all the measurement times and seasons (n = 9 per treatment).

Soil temperature was measured using temperature MicroLoggers (Hortplus, New Zealand) placed at a 5 cm depth 10 cm to left or right of the soil moisture sensor between mid-December 2019 and mid-August 2020. This spanned the first summer (mid-December to mid-March) and winter (mid-June to mid-August). The loggers measured temperature every 3 hours beginning at 12:01 pm. The measurements at 12:01:00 and 15:01:00 were defined as the day-time temperatures, and the measurements at 00:01:00 and 03:01:00 were defined as the night-time temperatures. Although loggers were placed in all kānuka pasture positions, 5 units malfunctioned, so 5 loggers measured at Wairarapa (2 in kānuka pasture and 3 in open pasture) and 8 measured at Hawkes Bay (3 in kānuka pasture and 5 in open pasture).

At each site an Onset Hobo RX3000 remote monitoring station (Onset Computer Corporation, USA), was installed in open pasture which recorded precipitation (mm), air temperature (°C), relative humidity (%) and wind speed (m s^{-1}). The rain gauge at Hawkes Bay malfunctioned during the trial so rainfall data for each year was used from a weather station 5.8 km from the site (station 2523) (CliFlo, 2021).

3.2.3 Statistical analysis

Mixed-effect models were used to compare to variables between treatments (kānuka pasture and open pasture) (Crawley, 2013; Zuur et al., 2009). Treatment was a fixed effect and site was a random effect. Interactions between treatment and site were also calculated. GDMP, dead matter, pH, sulphate-S, porosity 2–5 cm, available water capacity 2–5 cm, macroporosity 2–5 cm, bulk density 40–45 cm, VSM 0–60 cm, VSM 30–60 cm, summer VSM 0–30 cm and summer VSM 30–60 cm were tested without transformation as model residuals were approximately normal and their variances homogeneous after visual assessment (Crawley, 2013; Zuur et al., 2009). Green:dead matter ratio, pH, total-N, organic matter, CEC, K, Ca, Mg and Na were tested after being log-transferred so the model assumptions were met. Soil temperature was not statistically tested between treatments because of the reduced sample sizes after some of the sensors malfunctioned.

The multivariate canonical variate analysis (CVA) was then used to find the variables that best explained the variation between the treatment (kānuka pasture and open pasture) and sites (Wairarapa and Hawkes Bay), after the data were normalised (Jobson, 1996; Weihs, 1995). Variables that respond in a similar way in terms of how they impact pasture production were not duplicated in the CVA analysis because this distorts the model, overestimating the influence of the duplicated variables. Therefore, VSM 0–30 cm was used as the sole VSM measurement, CEC was used instead of all the cations because it is the summation of K, Na, Mg and Na and extractable acidity. K was kept in the analysis because it is often the most important cation for plant growth (McLaren and Cameron, 1996). Only topsoil soil physical variables were used because these likely had more influence on pasture growth than bulk density 40–45 cm, and pH was not included in the model because pH it was very similar between the treatments.

All the statistical analysis were done on R (v.4.1.1) (R Core Team, 2021). The 'lme4' package was used to make the mixed-effect model (Bates et al., 2015) and the 'candisc' package was used to do the CVA analysis and create the biplot (Friendly, 2021).

3.3 Results

3.3.1 Pasture production

On average between the two sites, there was 107.9% ($p < 0.001$) more GDMP in kānuka pasture than open pasture (Table 3.2). In year 1 and 2 there was 137.7% ($p < 0.001$) and 85.0% ($p < 0.001$) more GDMP in kānuka pasture, respectively. There was significantly more dead matter in open pasture ($p < 0.001$). There was a significant interaction for green:dead matter ratio ($p < 0.01$) between treatment and site (Figure 3.2).

Table 3.2. GDMP (Green dry matter production), dead matter and green:dead matter ratio for the treatments. The standard error of the mean is given in brackets.

Variable	Kānuka pasture	Open pasture	Significance
GDMP (kg ha^{-1} yr^{-1})	5541.0 (747.8) a	2665.8 (333.8) b	***
Dead matter (kg ha^{-1} yr^{-1})	681.8 (91.2) b	1014.8 (123.7) a	***
Green:dead matter ratio	8.8 (1.3) a	2.7 (0.2) b	***

Different letters represent significant differences between the treatments; *** $p < 0.001$ level.

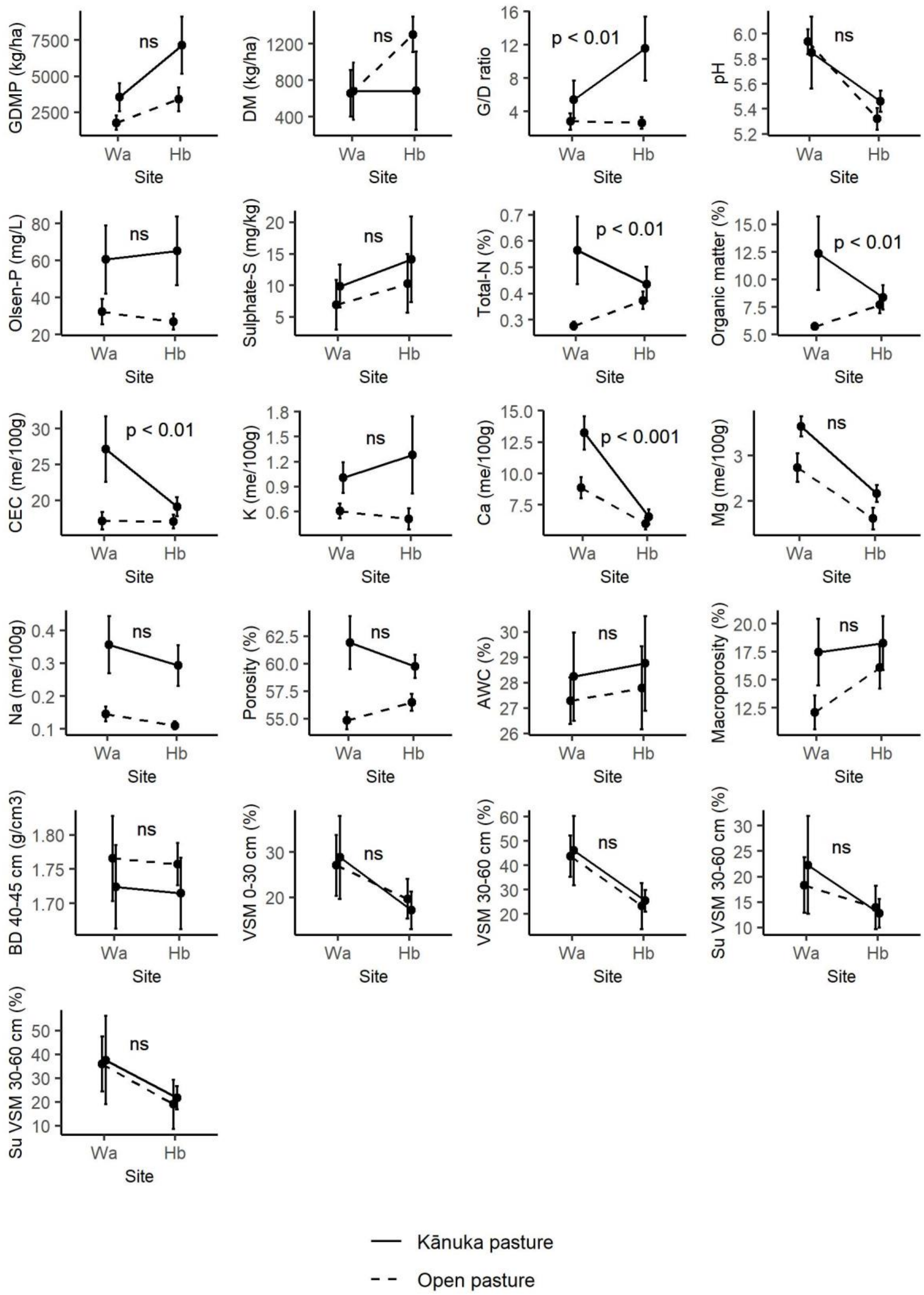

Figure 3.2. Pasture production and abiotic factor treatment and site interactions. The error bars are the 95% confidence intervals. Wa = Wairarapa. Hb = Hawkes Bay. GDMP = green dry matter production. DM = dead matter. G/D = green:dead. P = phosphorus. S = sulphur. N = Nitrogen. CEC = cation exchange capacity. K = potassium. Ca = calcium. Mg = magnesium. Na = sodium. Porosity = porosity 2–5 cm. AWC = available water content 2–5 cm. Macroporosity = macroporosity 2–5 cm. BD = bulk density. VSM = volumetric soil moisture. Su = summer.

3.3.2 Factors influencing pasture production

Rainfall in year 1 and 2 was 786 mm and 686 mm at the Wairarapa site, respectively, and 772 and 835 mm at a weather station 5.8 km from the Hawkes Bay site, respectively. The average temperature was 13.2 °C (min = -0.4 °C; max = 31.8 °C) and 14.1 °C (min = 0.3 °C; max = 37.1 °C) in year 1 and 2 at Wairarapa, respectively, and 12.5 °C (min = -2.5 °C; max = 34.6 °C) and 13.3 °C (min = 0.8 °C; max = 30.8 °C) at Hawkes Bay, respectively. The average windspeed at Wairarapa over two years was 1.3 m s^{-1} (min = 0.0 m s^{-1}; max = 16.4 m s^{-1}) and 2.5 m s^{-1} (min = 0.0 m s^{-1}; max = 16.0 m s^{-1}) at Hawkes Bay.

There was 67.2% LI under the kānuka trees at the Wairarapa site and 51.2% at the Hawkes Bay site. The minimum and maximum LI over the kānuka pasture positions at Wairarapa was 49.9% and 85.7%, respectively, and the minimum and maximum LI at Hawkes Bay was 23.5% and 88.0%, respectively.

The soil variables Olsen-P ($p < 0.001$), K ($p < 0.001$), Mg ($p < 0.01$), Na ($p < 0.001$) and Ca ($p < 0.05$) were significantly greater in kānuka pasture (Table 3.3). There was a significant interaction between site and treatment for total-N ($p < 0.01$), organic matter ($p < 0.01$) and Ca ($p < 0.001$) (Figure 3.2). Porosity 2–5 cm ($p < 0.05$) was also significantly greater in kānuka pasture (Table 3.3).

Table 3.3. Soil variable measurements for the treatments. The standard error of the mean is given in brackets.

Variable	Kānuka pasture	Open pasture	Significance
pH	5.6 (0.3) a	5.6 (0.3) a	ns
Olsen-P (mg L^{-1})	63.2 (5.6) a	29.3 (1.7) b	***
Sulphate-S (mg kg^{-1})	12.1 (1.7) a	8.8 (1.4) a	ns
Total-N (%)	0.5 (0.03) a	0.3 (0.01) a	ns
Organic matter (%)	10.1 (0.8) a	6.8 (0.3) a	ns
CEC (mg $100g^{-1}$)	22.7 (1.3) a	17.1 (0.3) a	ns
K (mg $100g^{-1}$)	1.2 (0.1) a	0.6 (0.04) b	***
Ca (mg $100g^{-1}$)	9.5 (0.1) a	7.3 (0.04) a	ns
Mg (mg $100g^{-1}$)	2.8 (0.2) a	2.1 (0.2) b	**
Na (mg $100g^{-1}$)	0.3 (0.02) a	0.1 (0.007) b	***
Porosity 2–5 cm (%)	60.6 (0.6) a	55.7 (0.3) b	*
Available water capacity 2–5 cm (%)	28.5 (0.6) a	27.6 (0.4) a	ns
Macroporosity 2–5 cm (%)	17.9 (0.8) a	14.3 (0.7) a	ns
Bulk density 40–45 cm (g cm^{-3})	1.72 (0.02)	1.76 (0.02) a	ns

Different letters represent significant differences between the treatments; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ level; ns = not significant. P = phosphorus. S = sulphur. N = nitrogen. CEC = cation exchange capacity. K = potassium. Ca = Calcium. Mg = Magnesium. Na = sodium.

There were no significant differences between treatments for any VSM variables, nor significant interactions (Table 3.4). At no point did the soil exceed field capacity at either site during the study as the VSM was never greater than the porosity at any position between 0 cm and 30 cm.

Table 3.4. Volumetric soil moisture (VSM) for the treatments. The standard error of the mean is given in brackets.

Variable	Kānuka pasture	Open pasture	Significance
VSM 0–30 cm (%)	23.0 (2.5) a	22.3 (1.8) a	ns
Summer[a] VSM 0–30 cm (%)	17.0 (6.4) a	15.9 (3.9) a	ns
VSM 30–60 cm (%)	33.2 (4.0) a	33.5 (4.3) a	ns
Summer[a] VSM 30–60 cm (%)	27.7 (9.6) a	27.5 (11.1) a	ns

Different letters represent significant differences between the treatments; ns = not significant.
[a] Summer = VSM measurements between 15th December and 14th March.

The mean day soil temperature in the first summer at Wairarapa under and away from the trees was 20.6 °C (min = 14.8 °C; max = 26.4 °C) and 25.5 °C (min = 16.9 °C; max = 36.5 °C), respectively, and at Hawkes Bay it was 19.2 °C (min = 12.3 °C; max = 26.7 °C) and 21.9 °C (min = 13.5 °C; max = 30.5 °C), respectively. The mean night soil temperature in the first winter at Wairarapa under and away from the trees was 11.3 °C (min = 4.0 °C; max = 19.1 °C) and 12.4 °C (min = 4.5 °C; max

= 26.4 °C), respectively, and at Hawkes Bay it was 11.1 °C (min = 4.5 °C; max = 19.1 °C) and 11.1 °C (min = 4.5 °C; max = 19.3 °C), respectively. The mean day soil temperature in the first winter at Wairarapa under and away from the trees was 13.2 °C (min = 6.6 °C; max = 22.9 °C) and 14.3 °C (min = 6.4 °C; max = 23.0 °C), respectively, and at Hawkes Bay it was 12.9 °C (min = 5.1 °C; max = 22.8 °C) and 13.2 °C (min = 5.0 °C; max = 23.0 °C), respectively.

3.3.3 Canonical variate analysis

The Canonical Variate Analysis (CVA) explained 92.2% of the total variation between the treatments and sites (Figure 3.3). The Wilks' lambda was significant ($p < 0.001$). Canonical variate 1 explained 72.3% of the variation ($p < 0.001$) and Canonical variate 2 explained 19.9% ($p < 0.05$). Canonical variate 3 explained 7.8% of the variation ($p > 0.05$). The first canonical variate discriminated the data per treatment (kānuka pasture and open pasture) (x-axis) and Canonical variate 2 discriminated the treatments per site (Wairarapa and Hawkes Bay) (y-axis). Olsen P, K and porosity were the environmental variables most strongly positively associated with kānuka pasture. VSM 0–30 cm was most strongly positively associated with the Wairarapa site. GDMP was most strongly positively associated with kānuka pasture at the Hawkes Bay site.

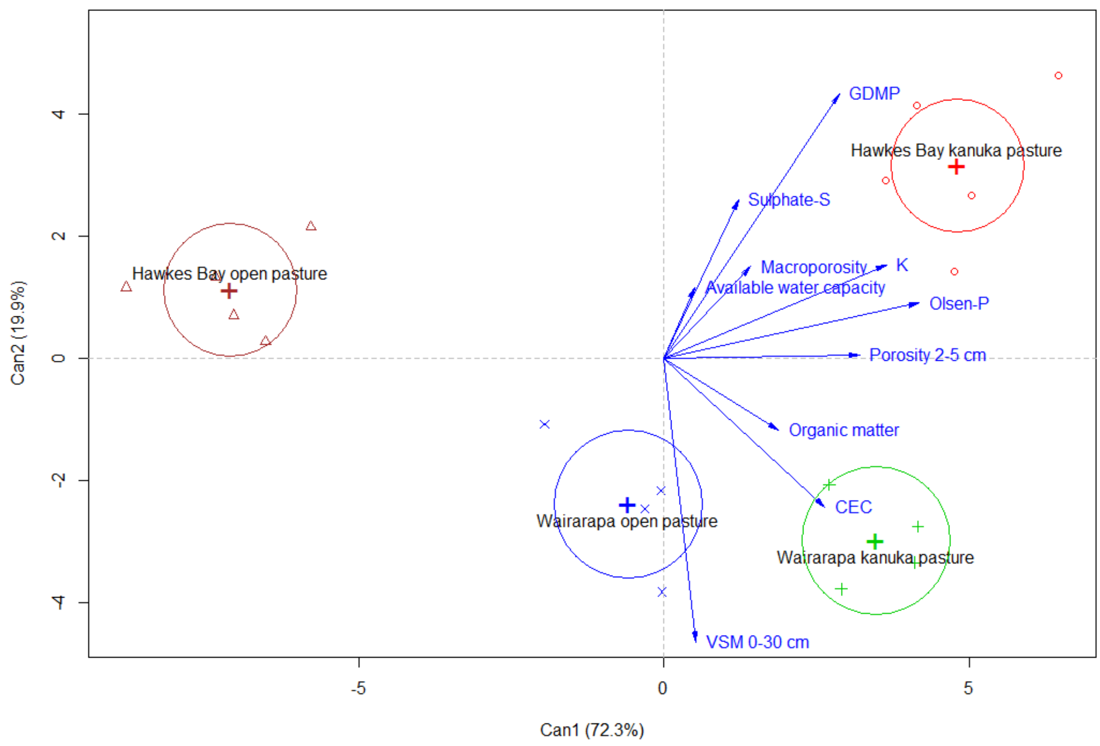

Figure 3.3. Canonical variate analysis showing which variables best explain treatment and site differences. GDMP = Green dry matter production. P = phosphorus. S = Sulphur. K = potassium. CEC = cation exchange capacity. VSM = volumetric soil moisture.

3.4 Discussion

The 107.9% greater green dry matter production under kānuka silvopastoral trees shows that the genus has potential to increase pasture production of low producing sloped areas of New Zealand hill country. This result is contrary to past silvopastoral research in hill country, with no published studies finding more pasture production under mature trees in hill country compared to equivalent areas of open pasture (Benavides et al., 2009; Devkota et al., 2009; Power et al., 1999). This study gives evidence that kānuka may function differently to poplar as a silvopastoral tree, and that trees in hill country can significantly increase pasture production under their canopy in certain situations. Nevertheless, there are many limitations with this study that will be explored below, such as these results could be as a result of a site specific effect as there was evidence of a strong compounded livestock effect, and there may not have been a net increase in pasture production at the paddock scale . Therefore, more research is required to confirm these results on other farms and validate whether kānuka does have potential to increase pasture production on hill country farms.

3.4.1 Soil nutrients

It is widely documented that silvopastoral trees can improve soil fertility under their canopies (see Marañón et al., 2009), with there being many examples from oak silvopastoral systems in Southern Europe (e.g. Gallardo, 2003; Howlett et al., 2011; Moreno Marcos et al., 2007; Rossetti et al., 2015) and California (e.g. Callaway et al., 1991; Dahlgren et al., 1997; Marañón and Bartolome, 1994). Soil nutrient increases under trees have been as high in past studies as in this one, with Dahlgren et al. (1997) finding 55–60% more organic carbon and N pools under an oak canopy in California. Moreover, Rossetti et al. (2015) found over 50% more organic matter and available P under oak canopies in Italy.

Olsen-P and K levels were very high under the trees when compared to previous poplar silvopastoral work (Guevara-Escobar et al., 2002; Wall, 2006), past hill country research of medium and high sloped areas (López et al., 2003b), and research established optimum levels for maximising hill country pasture growth (Morton and Roberts, 2018). Moreover, these soil variables were strongly positively associated with kānuka pasture in the CVA. One likely mechanism contributing to these greatly elevated nutrient levels is livestock depositing and concentrating urine and dung in the kānuka pasture environment (Marañón et al., 2009).

This could be happening for two reasons. Open pasture at both sites were exposed to strong winds and sun, and the tree-pasture environment likely represented a sheltered and shaded environment. Secondly, pasture could have been preferentially grazed in kānuka pasture. López et al. (2003a) has previously provided evidence that perennial ryegrass is preferentially grazed in hill country, and the greater pasture production under the trees at both these sites has been shown to be the result of the growth of more productive pasture species such as perennial ryegrass (Mackay-Smith et al. *submitted*).

Livestock nutrient transfer for P and S by livestock from medium and high sloped hill country areas to low sloped areas has been shown by Saggar et al. (1990), and nutrient transfer is one of the main reasons for the poorer soil conditions and reduced pasture growth in steeper areas of hill country (López et al., 2003b; Saggar et al., 1990). Therefore, this study gives evidence that nutrient transfer by livestock could also potentially occur from open pasture areas to tree pasture areas, and trees might be able to be used as a tool for nutrient transfer and spatial distribution.

Another factor that could be contributing to a build-up of organic matter under the silvopastoral trees in addition to livestock dung deposition is tree litterfall. Litterfall in mānuka-kānuka scrub (mānuka (*Leptospermum scoparium* J.R.Forst. & G.Forst.) is a tree in the same family as kānuka and both often grow together in mixed shrubland) has been shown to add 1941–2488 kg ha^{-1} yr^{-1} of carbon and 28–37 kg ha^{-1} yr^{-1} of N to the soil (Lambie and Dando, 2019). This study was in a 'high-density' (no density was given in the study) unmanaged stand that also had forest undergrowth, so the system studied by Lambie and Dando (2019) would have most likely added more litter than individually spaced kānuka trees in a silvopastoral system. Nevertheless, this gives evidence that kānuka trees should add organic matter and N to the soil.

The interaction between site and treatment for organic matter shows that there was over 50% more organic matter in kānuka pasture compared to open pasture at Wairarapa, but organic matter was similar between treatments at Hawkes Bay (Figure 3.3). This could be because organic matter had reached an optimum level in in both kānuka pasture and open pasture at Hawkes Bay, but not at Wairarapa. This may also explain why GDMP was lower in open pasture at Wairarapa when compared to open pasture at Hawkes Bay.

Other reasons reported in past literature for trees increasing the availability of nutrients under silvopastoral trees include nutrient enrichment of throughfall by the tree canopy (Callaway et al., 1991; Catriona et al., 2012; Veneklaas, 1990), or the addition of mycorrhizal fungi in the soil facilitating nutrient uptake by pasture (He et al., 2003; Querejeta et al., 2007). Although mycorrhiza activity has been shown to be negatively impacted by high increasing soil phosphorus levels (Deng et al., 2017), so mycorrhiza activity may not be a significant factor at the studied sites.

3.4.2 Soil water and structure

In terms of soil water, trees can facilitate water availability improvements by adding shade and reducing wind run, which can reduce evapotranspiration and water loss from the soil (Bahamonde et al., 2009; Marañón et al., 2009; Peri, 2005). Trees can also modify soil physical properties via their impact on soil organic matter which can lead to increased water retention (Joffre and Rambal, 1988), and hydraulically uplift water from lower soil layers (Kurz-Besson et al., 2006; Ludwig et al., 2004), which could increase the availability of soil moisture to pasture. Yet trees also take up water, depleting available water resources for plant growth (Guevara-Escobar et al., 2000; Wullschleger et al., 1998), and intercept rainfall, reducing the amount of rainfall reaching the soil (Guevara-Escobar et al., 2000). Nevertheless, the VSM results give evidence that the kānuka were not outcompeting pasture for VSM, but they were also not conserving VSM compared to open pasture. This result is positive because it shows that the tree water use, or rainfall interception, were not having overriding negative influences on the system and negatively impacting pasture production.

The improvements in porosity may have contributed to pasture production improvements directly, as improvements to porosity can increase the growth roots (Burgess et al., 2000; Harrison et al., 1994), and facilitate root aeration (Chapman and Allbrook, 1987; McLaren and Cameron, 1996). Because of the evidence that trees provided shelter to livestock under the trees, it is surprising that this did not result in soil compaction because it is well established how increased livestock activity can result in negative impacts to soil physical properties (Houlbrooke et al., 2021; Koppe et al., 2021; Zhang et al., 2019). For example, Zhang et al. (2019) found porosity increased from 0.64 to 0.78 when the grazing intensity was reduced from 4.8 animal unit months ha^{-1} to 1.2 animal unit months ha^{-1} in Canadian pastoral land. This soil physical results of this present study therefore indicate that the potential livestock activity under the trees was not intensive enough to result in negative impacts to soil structure.

3.4.3 Tree bio-physical attributes

The conclusion in past poplar studies is that light was the main limiting factor to pasture growth in studies that have measured less pasture production under poplar in wetter and drier areas of sloped hill country (Douglas et al., 2001; Guevara-Escobar et al., 2007; Wall et al., 2006). The results of this present study questions this conclusion because following that reasoning, pasture production should have also been less under the kānuka trees because there was on average 67.2% and 51.2% light interception by the trees at Wairarapa and Hawkes Bay, respectively. Therefore, this is evidence that the contrasting bio-physical attributes of poplar were leading to reduced pasture production reported in past studies (Benavides et al., 2009), and not light reductions.

Past poplar studies have found that the trees do show consistent improvements to soil Olsen-P levels compared to open pasture (Guevara-Escobar et al., 2002; Wall, 2006). The contrasting results in this study could be a result of differing livestock interactions under poplar and kānuka canopies. Kānuka is a much smaller tree than poplar and has a more sheltered environment (Mackay-Smith et al., 2021). As such, livestock may prefer to spend more time under kānuka compared to poplar, resulting in more P nutrient transfer to kānuka pasture positions (López et al., 2003b; Saggar et al., 1990). Moreover, kānuka are evergreen and poplar are deciduous, which means kānuka could potentially facilitate more livestock use under tree canopies throughout the year.

There is evidence that poplar reduce soil moisture compared to open pasture, with Douglas et al. (2001) reporting 33% reductions of soil moisture under poplar in a summer and autumn drying phase compared to open pasture. Moreover, Guevara-Escobar et al. (2007) also found more some evidence of less soil moisture between 0–30 cm in late summer (March) under poplar trees compared to open pasture. The similar VSM measurements in summer in this present study are encouraging because it gives evidence that kānuka are potentially not depleting soil moisture in summer compared to open pasture.

The age of the kānuka and poplar systems may have also had differing impacts on pasture and soil outcomes. The kānuka trees at Wairarapa were at least 80 years old, and they were most likely also at least this age at the Hawkes Bay site. However, the mature poplar trees studied by Guevara-Escobar et al. (2002) that did not increase organic matter, or N or P levels were 29 year olds or 40 years old. The Olsen-P, K and porosity improvements under the kānuka trees in this present study could have been the result of compounded positive influences on the system over time. Poplar might not have shown this effect because the systems were not as old as the kānuka in this present study. Nevertheless, with the recommended practice being to fell poplar trees after 40 years because of branch break damage (Charlton et al., 2007), if the positive impacts on the pasture and soil were because of the long-term impacts on the soil and pasture, this would likely not happen in a poplar silvopastoral system.

Finally, poplar may have directly negatively impact pasture production through their leaf fall smothering grass in autumn (Douglas et al., 2006; Kemp et al., 2018). As the leaf fall of kānuka is spread throughout the year (Lambie and Dando, 2019), and their leaves are smaller than poplar, litterfall should potentially have less of a negative impact on pasture production in a kānuka silvopastoral system.

A facet not investigated is the influence of silvopastoral trees in different climates. Rivest et al. (2013) provides evidence that the relationship between the impact of silvopastoral trees on pasture production and annual precipitation depends on tree type. The authors found a negative linear relationship between effect size on pasture production and annual average precipitation for

N-fixing silvopastoral trees, but a positive linear relationship for eucalyptus (Rivest et al., 2013). This highlights how trees with different attributes can result in contrasting pasture production outcomes. The impact of kānuka on pasture production could therefore vary depending on rainfall, and thus have a different climate-production relationship compared to poplar.

3.4.4 Implications

It is important to recognise that this study is the first time to measure the influence of kānuka on the soil and pasture. New Zealand pastoral land is a highly variable landscape with contrasting soil types, climates, topographies, aspects, management types and livestock types. The impact of kānuka on pasture will most likely vary with these conditions. More work is required on other farms in these different conditions to form generalised conclusions for how kānuka performs as a silvopastoral tree in hill country.

Moreover, if the only mechanism occurring was livestock nutrient transfer within the paddock, there may not have been a net build-up of fertility within the whole paddock, and the transfer of nutrients away from the open pasture positions could have diminished pasture production in these positions. More research is required confirm whether kānuka does result in a net increase in fertility and pasture production at paddock scale.

Another caveat is livestock camping areas were specifically avoided in tree selection. These livestock camping areas are likely a result of the silvopastoral tree design and livestock management. More work is required to understand the dynamics of livestock management and camping areas in hill country, and how they might impact the overall potential positive impacts of kānuka on pasture production at farm scale.

Furthermore, trees were selected at each site based on their close proximity to other individually spaced kānuka trees and equivalent of open pasture areas because of equipment constraints. It is possible trees growing closer together may have resulted in different livestock interactions or tree influences compared to more isolated silvopastoral trees. Nevertheless, from visual observation of the silvopastoral environments at both sites, the environment studied represented the typical agricultural environment under the kānuka trees that did not have livestock camping spots.

The lack of research showing positive interactions between trees and pasture production in New Zealand hill country (Benavides et al., 2009), in addition to studies that have shown negative relationships between light and pasture production reductions for poplar and radiata pine (*Pinus radiata* D. Don) (Knowles et al., 1999; Wall et al., 2006), has resulted in a narrative that trees in general negatively impact pasture production in New Zealand hill country. The results of this present study questions this narrative because this is the first published study to find increased pasture production under mature silvopastoral trees in New Zealand hill country (Benavides et al., 2009; Devkota et al., 2009; Kemp et al., 2018; Power et al., 1999). Research on poplar and radiata pine cannot be extrapolated to other silvopastoral tree genera or species, especially if they have contrasting bio-physical tree attributes (Mackay-Smith et al., 2021).

Furthermore, this study shows that there is potential for silvopastoral systems in New Zealand to provide a range of environmental benefits to agricultural land in terms of slope stability, biodiversity conservation and carbon sequestration (Dominati et al., 2019; Mackay-Smith et al., 2021; Spiekermann et al., 2022), in addition to providing significant improvements to soil condition and pasture production. Multifunctional silvopastoral landscapes are therefore possible in hill country, and continued work on facilitative silvopastoral genera is fundamental to better understand why some silvopastoral trees have the potential to improve pasture production outcomes, but others do not. When this can be understood, silvopastoral systems can then be designed to optimise pasture production outcomes, and maximise the positive impacts of these systems to pastoral landscapes.

3.5 Conclusion

Over a two-year period at two sites, this study measured how a novel silvopastoral system in New Zealand with kānuka, that has similar bio-physical attributes to the ñire forests of southern Patagonia, and the oak silvopastoral systems of southern Europe and California, influences pasture production and pasture-soil relationships. There was 107.9% more pasture production in kānuka pasture positions, and Olsen-P, porosity and K best explained the variation between kānuka pasture and open pasture positions. VSM was similar in kānuka pasture and open pasture positions. The high concentration of Olsen-P and K in kānuka pasture gives evidence of nutrient transfer to the tree-pasture environment. Moreover, there was 48.6% more organic matter under the trees and a significantly greater porosity, which is evidence that other processes were also contributing to soil organic matter levels in the kānuka pasture environment, such as litterfall.

The disparity between the results of this study and previous studies on poplar in New Zealand hill country show that trees with different bio-physical attributes to poplar could be important for increasing pasture production and improving soil conditions compared to open pasture. Moreover, these results are evidence that kānuka may have potential as a silvopastoral tree for forming transformative multifunctional landscapes, potentially adding both environmental and economic value to New Zealand hill country farms. Nevertheless, more research is required to confirm these results on other farms because of the limitations in this study.

Chapter 3 summary

This chapter explored hypothesis 1 and measured how kānuka impacts pasture production, and discriminated which variables contributed to pasture production differences under and away from the trees. The study found kānuka to increase pasture production by over 100% at two sites, indicating there could be potential for kānuka silvopastoral systems to overcome economic and environmental trade-offs in New Zealand hill country. However, more research is required to validate these findings on other farms to confirm the systems potential.

Chapter 4 Pasture ecological functionality in a kānuka silvopastoral system

Using a functional ecology perspective, this chapter explores hypothesis 2 by measuring the ecological mechanisms for how a kānuka silvopastoral system impacts pasture production and pasture stability. Together, Chapter 3 and Chapter 4 form a detailed look into how a kānuka silvopastoral system impacts pasture functionality in New Zealand hill country.

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4.1 Introduction

How silvopastoral systems impact the growth of different pasture species is integral for their management because in less-intensive and low producing diverse grasslands, pasture production can be a direct result of the pasture species that grow (López et al., 2006; Marañón and Bartolome, 1994). Moreover, measuring how silvopastoral trees impact diversity is important because the presence of different species with multiple functions in the same community has been shown to increase the stability of grasslands, in terms of their response to stress (Frank and McNaughton, 1991; Tilman and Downing, 1994; Tracy and Sanderson, 2004). Grouping species into functional groups that respond in a similar way to the environment helps discriminate which groups of species are impacting production and stability outcomes in the pastoral system (Gitay and Noble, 1997; Hector et al., 1999; López et al., 2006; Zhang et al., 2005). Nevertheless, there is limited information on how silvopastoral systems impact the production and stability of grasslands from a functional ecology perspective.

Past research has typically found silvopastoral systems reduce species diversity compared to open pasture (Fernández-Moya et al., 2011; López-Carrasco et al., 2015; Marañon, 1986; Rossetti et al., 2015), however, it is the impact of this diversity loss on production and stability outcomes that is important from a production management perspective. Many studies have measured how silvopastoral trees impact pasture species percentage cover (Fernández-Moya et al., 2011; López-Carrasco et al., 2015; Marañon, 1986; Rossetti et al., 2015; Treydte et al., 2009), although percentage cover abundance is not necessarily a good approximation for production outcomes in pastoral systems (Chiarucci et al., 1999). Some studies have measured how the production of different species varies under and away from trees (Douglas et al., 2006; Guevara-Escobar et al., 2007; Marañón and Bartolome, 1994), and many have put pasture species into course functional groups such as grasses, forbs or legumes (e.g. Buergler et al., 2005; Douglas et al., 2006; López-

Carrasco et al., 2015). Nevertheless, not considering species group dynamics in terms of function misses the mechanisms for how trees impact production and stability in the system.

The mass ratio hypothesis suggests that the traits of dominant species drives ecosystem functionality, and total production is relatively insensitive to species richness changes (Grime, 1998). Many studies have found evidence for this (Abul-Fatuh and Bazzaz, 1979; Hooper and Vitousek, 1997; MacGillivray et al., 1995; Roscher et al., 2007; Sonkoly et al., 2019; Wardle et al., 1997). In terms of silvopastoralism, although the author did not measure pasture biomass, Marañon (1986) found a greater percentage cover of *Dactylis glomerata* L. under oak trees (*Quercus* spp.) in a Spanish *dehesa* site dominated by annuals, and hypothesised that this was because of more moisture availability in early summer under trees (Joffre and Rambal, 1988; Marañón and Bartolome, 1994), in addition to increased nitrogen availability. *Dactylis glomerata* is a dominant and productive grass (Grime et al., 1988; Gurevitch and Unnasch, 1989; Rice and Nagy, 2000), so Marañon (1986)'s study shows that facilitative silvopastoral tree-effects could increase total pasture production by promoting the growth of fast-growing and competitive functional groups. Moreover, it indicates that reductions to species richness in silvopastoral systems may not impact production outcomes.

How the growth of more productive species impacts species diversity is also important for pasture stability (Frank and McNaughton, 1991; Tilman and Downing, 1994). Even if silvopastoral trees increase the biomass growth of a few dominant species, the potential loss of species diversity under silvopastoral systems could have negative impacts to pasture stability. This could be especially so in high fertility environments common under silvopastoral trees (Gallardo, 2003; Rossetti et al., 2015), as fertilised meadows have been shown to not sustain high diversity levels (Plantureux et al., 2005). Nevertheless, stability has also been shown to be related to the growth of specific plants with stress tolerant traits (Sankaran and McNaughton, 1999; Tracy and Sanderson, 2004), therefore, stability is not necessarily related to species diversity, which has been the focus of past silvopastoral research (Fernández-Moya et al., 2011; López-Carrasco et al., 2015; Marañon, 1986; Rossetti et al., 2015). Even if facilitative silvopastoral trees increase pasture production through the growth of a smaller number of competitor functional groups, if the silvopastoral environment maintain functional groups with stress tolerant traits, this could mean pasture stability is maintained or improved, despite a loss to species diversity.

Despite not being used in past silvopastoral research, measuring functional diversity (FD) accounts for the potential functional homogenisation (Aguirre-Gutiérrez et al., 2017) and functional redundancy of species in the system (Feng et al., 2020; Grime, 1998; Mason et al., 2005; Sonkoly et al., 2019). Solely considering species diversity metrics may give misleading interpretations because as explained above, species diversity reductions does not necessarily impact stability functionality.

This study will measure production and stability in the context of functional ecology in New Zealand hill country. Hill country is an economically important agricultural area in New Zealand (Beef + Lamb, 2020a, 2020b; Kemp and López, 2016), which covers around 5.2 million hectares (20.5% of New Zealand's land mass) (Mackay, 2008). It is defined as having steep or hilly land (> 15°), being below 1000 m asl and having pastoral farming as its main land use (sheep, cattle and deer) (Dodd et al., 2016; Kemp and López, 2016). Many areas of hill country have a low production (Lambert et al., 1986a; López et al., 2003a, 2003b), with slope being one of the main drivers determining soil-water dynamics and the presence and abundance of pasture species and their performance (Lambert et al., 1986a, 1986b; López et al., 2006; Nicholas, 1999). Trees may be a valuable way of improving the production and stability of these sloped areas.

López et al. (2006) previously derived species functional groups for hill country pastures, with the groups *Lolium perenne* L. and high fertility grasses having the greatest biomass in low slope and high fertility/stocking rate treatments, and low (e.g. *Rytidosperma* spp, *Festuca rubra* L. and *Hypochaeris radicata* L.) and medium (e.g. *Anthoxanthum odoratum* L. and *Cynosurus cristatus* L.)

fertility species having the greatest biomass in high slope and low fertility/stocking rate treatments. Because these functional groups have already been derived via multivariate statistics (López et al. 2006), New Zealand hill country is an great place to measure silvopastoral pasture production and stability outcomes in terms of functional ecology.

This study examines a silvopastoral system in New Zealand hill country with kānuka (*Kunzea* spp.). Kānuka is a native genus that has 10 endemic species in New Zealand (de Lange, 2014). It is locally very common in hill country (Bergin et al., 1993; Spiekermann et al., 2021), and has great potential as a silvopastoral tree because of its potentially reduced water use compared to the typical silvopastoral trees that have been researched and are planted in in hill country (poplar (*Populus* spp.)) (Boffa Miskell Limited, 2017; Guevara-Escobar et al., 2000; Mackay-Smith et al., 2021; Wullschleger et al., 1998), that it is evergreen, so it will provide shelter to livestock and litterfall year-round, and its longevity, so any facilitative effects should be compounded over time (Mackay-Smith et al., 2021; Mackay-Smith et al., 2022). No study has measured how kānuka impacts pasture diversity or stability in a silvopastoral system. Because of the potential facilitative effects of kānuka as a silvopastoral tree, we hypothesise that 1) total pasture production is greater under kānuka because of the growth of more competitive and fast-growing perennial species, 2) this does not negatively impact pasture stability because the trees should promote the growth of a range of functional pasture groups, despite a loss in species richness, and 3) FD indices give a better indication of true diversity changes than species diversity indices.

4.2 Methods

4.2.1 Site characteristics

Two sites were selected to study with similar climates, soil types and livestock operation to increase the reliability of the results. One site was in the Wairarapa region, ~10 km north of Martinborough (Wairarapa site) (41°08’41.3”S, 175°29’58.3”E, 122 m), and another in the Hawkes

Bay region, ~20 km south of Waipukurau (Hawkes Bay site) (40°08′25.9″S, 176°23′39.1″E, 288 m). The Wairarapa site is underlain by sandstone and the Hawkes bay site is underlain by mudstone. The soil type at both sites is a Mottled Argillic Pallic Soil in the New Zealand classification (Hewitt, 2010), and a Ustalf in the USA soil classification (Hewitt, 2010). The topsoil type at both sites is a silt loam. The subsoil type (B horizon) at both sites is a silty clay loam.

The mean 30-year annual rainfall at Wairarapa was 903 mm (min: 548 mm; max: 1297 mm; Station 2631; 6.6 km from the site, elevation: 58 m) (CliFlo, 2021), and 883 mm at Hawkes bay (min: 527 mm; max: 1483 mm; Station 2523; 5.8 km from the site, elevation: 153 m) (CliFlo, 2021). The mean 10-year annual temperature at Wairarapa was 18.3 °C (min: 17.5 °C; max: 19.0 °C; station 21938; 15.0 km from the site, elevation: 22 m) (CliFlo, 2021), and 16.7 °C at Hawkes Bay (min: 15.8 °C; max: 17.5 °C; Station 25820, 15.3 km from the site, elevation: 341 m) (CliFlo, 2021).

Both sites were in permanent and naturalised pasture on typical commercial sheep and beef farms of the region. The paddock topography at Wairarapa was moderately to severely steep (15–40°) and it was rolling to moderately steep (10–30°) at Hawkes Bay. The aspect of the site at Wairarapa was northeast, and it was northwest at Hawkes Bay. Individual *Kunzea robusta* de Lange et Toelken (kānuka) trees grew in the study site paddocks at densities that ranged from ~10 trees ha^{-1} to ~2000 trees ha^{-1}. The land was most likely cleared for grazing 100–200 years ago and after this the trees likely established as seedlings.

Figure 4.1. Some of the kānuka trees evaluated in the study. A: Shows two of the evaluated trees at Hawkes Bay. B: Shows some of the evaluated trees at Wairarapa. Both photographs were taken by the lead author.

The paddock at Wairarapa was rotationally grazed for 2 days to 3 days at a time over the course of the year. The grazing intensity at the site was 57 ewes ha^{-1} day^{-1}, lambs at 40 lambs ha^{-1} day^{-1}, Angus cows at 9.1 cows ha^{-1} day^{-1} and Friesian bulls at 3.4 bulls ha^{-1} day^{-1}. The paddock at Hawkes Bay was set stocked for about 1 month by pregnant ewes during lambing at a stocking rate of 5.7 ewes ha^{-1} and then rotationally grazed for one week at a time by Angus cows at a grazing intensity of 0.8 cows ha^{-1} day^{-1}. Annual fertilisation to the paddock at Wairarapa has been 21.5 kg P ha^{-1} and 37 kg S ha^{-1}, which has been surface applied in spring or early summer. The annual fertiliser rates at Hawkes Bay have either been 25.8 kg P ha^{-1} and 42 kg S ha^{-1}, or 25 kg N ha^{-1} and 28.75 kg S ha^{-1}, which have been surface applied in winter. There have also been some years where no fertiliser was applied at Hawkes Bay because of high Olsen-P soil tests.

The study had two treatments replicated at each site. 'Kānuka pasture' silvopastoral measurement positions were under individually spaced kānuka tree canopies (half-way between the canopy edge and stem) (Guevara-Escobar et al., 2002). 'Open pasture' measurement positions were in paired open pasture positions with similar slope position, slope gradient and characteristics at least 15 m from the nearest tree trunk. A 15 m distance from the tree trunk was chosen because there was a ~5 m distance between the trunk and the drip line (edge of canopy) for each studied tree, and Howlett et al. (2011) selected a distance of a three times the drip line for open pasture positions. All positions were on slope gradients between ~20° and ~25°. There were nine tree replicates in total, four at the Wairarapa site and five at the Hawkes Bay site. The trees at Wairarapa were over 80 years old, which was confirmed with historic aerial imagery (Retrolens, 2021). The age of the trees at Hawkes Bay is unknown, however, the trees were also likely to be > 80 years old because the trees at this site are larger than the ones at Wairarapa. The heights of the studied trees were ~10 m at Wairarapa and 10–15 m at Hawkes Bay.

As 5 m to 20 m long soil moisture sensors connected to a central data logger were to be installed permanently at both sites, trees in each paddock were selected based on there being open pasture and four or five individual kānuka trees in close proximity of each other. Moreover, in each study paddock, there were a few trees that had livestock camping spots on the downslope side of the trees. These were avoided as study trees during site selection.

Measurements for the study were taken from 12th December 2019 until 11th December 2021. At each position, total dry matter production, dry mater production per each individual species or species group, soil moisture, soil physical properties, soil fertility and light interception were measured.

4.2.2 Pasture measurements

The pre-trimmed exclusion technique was used to measure accumulated pasture production of each pasture species (Radcliffe et al., 1968). One pasture cage per position was used to measure pasture production at each position (n = 9 per treatment). Following pre-trimming to 1 cm using electric clippers within the pasture cage area (López et al., 2003b), pasture was harvested after a ~2-month regrowth period (the regrowth period varied depending on the season). Each site was harvested on the same day or on consecutive days. Pasture was harvested from a 25 cm x 50 cm quadrat within the pasture cage area after being cut to 1 cm in height. The cage was then placed in a new pre-trimmed pasture spot within the same position and rotated between 3 pasture cage spots within each position during the study. This allowed livestock behaviour to continue within the sampling locations throughout the study. Different positions were used if there were obvious dung or urine deposits in a cage position. Each sample was oven-dried for 72 hours at 70 °C and weighed. Every season a subsample was taken and identified into individual pasture species and dead matter. These individual pasture species groups and dead matter were also oven-dried for 72 hours at 70 °C and weighed. Each season, the proportions of each species and dead matter were used to calculate total green dry matter production (kg DM ha^{-1} yr^{-1}) of individual pasture species and total production.

Pasture species functional groups were formed based on the functional groups described by López et al. (2006). There are several differences, however, between the functional groups in this present study and López et al. (2006). In this present study, *D. glomerata* was considered in its own group due to its distinctive morpho-physiological attributes, such as deep roots, drought tolerance and shade tolerance (Joshi, 2000; Koukoura and Kyriazopoulos, 2007; Mosquera-Losada et al., 2006), and its high proportion of total production in relation to the other grasses at the sites. High fertility annual grasses (HFA) were a separate group in this study because of their prevalence in this study, and their importance in other silvopastoral systems (López-Carrasco et al., 2015; Marañon, 1986). Dicotyledons (dicots) were placed in their own group, formed of species such as, *Plantago lanceolata* L., *Hypochaeris radicata* L., *Crepis capillaris* (L.) Wallr., *Lamium amplexicaule* L. and *Cirsium arvense* (L.) Scop., all of them naturally belonging to a uniform group of dicotyledons herbs. Our low presence species (LP) group was defined as having an overall percentage composition of less than 1% in each treatment. The following functional groups were therefore defined: *L. perenne*, *A. capillaris, D. glomerata,* high fertility annual grasses (HFA), medium fertility species (MFS), low fertility tolerant grasses (LF), dicotyledons (dicots) and low presence species (LP) (Table 4.1).

Table 4.1. Pasture functional groups used in the data analysis.

Functional group	Species Latin name	Species common name
Lolium perenne	*Lolium perenne* L.	Perennial ryegrass
Dactylis glomerata	*Dactylis glomerata* L.	Cocksfoot
Agrostis capillaris	*Agrostis capillaris* L.	Browntop
Medium fertility species (MFS)	*Anthoxanthum odoratum* L.	Sweet vernal
High fertility annual grasses (HFA)	*Bromus hordeaceus* L.	Soft brome
	Critesion murinum (L.) Á.Löve	Barley grass
Low fertility tolerant grasses (LF)	*Rytidosperma* spp.	Danthonia spp.
	Vulpia bromoides (L.) Gray	Vulpia hair grass
Dicotyledons (Dicots)	*Hypochaeris radicata* L.	Catsear
	Plantago lanceolata L.	Narrowleaf plantain
	Other dicotyledons	
Low presence species (LP)	*Carex* spp.	Sedges
	Cirsium arvense (L.) Scop.	Creeping thistle
	Crepis capillaris (L.) Wallr	Smooth hawksbeard
	Cynosurus cristatus L.	Crested dogstail
	Holcus lanatus L.	Yorkshire fog
	Juncus spp.	Rushes
	Lamium amplexicaule L.	Common henbit
	Sporobolus africanus (Poir.) Robyns & Tournay	Ratstail
	Trifolium dubium Sibth.	Suckling clover
	Trifolium glomeratum L.	Clustered clover
	Trifolium pratense L.	Red clover
	Trifolium repens L.	White clover
	Trifolium subterraneum L.	Subterranean clover

4.2.3 Soil and climatic measurements

Continuous measurements of volumetric soil moisture (VSM) were taken using one time domain reflectometry soil moisture sensor in each position (n = 9 per treatment). The sensors measured VSM every 30 minutes between 0 cm and 30 cm, and were installed vertically (CS616 – sensor length 30 cm, Campbell Scientific, USA). They were installed in the centre of each position. Data were stored on site using Campbell Scientific data loggers. Two data loggers were installed at Wairarapa (Campbell Scientific CR800 and Campbell Scientific CR1000) and one was used at Hawkes Bay (Campbell Scientific CR1000). Two Campbell Scientific 16/32B multiplexers were used to extend the cable lengths at Hawkes Bay. All data loggers were connected to a 12 V battery and charged with a solar panel, that were housed in waterproof electrical boxes. One VSM measurement per position was calculated by averaging all the VSM measurements over the period.

For the soil fertility analysis, ten soil cores (0–7.5 cm) were systematically sampled from a pasture cage spot within each position in December 2019 and December 2021. Cores were also samples in December 2020 from the third pasture cage spot, but this sample was not analysed as two repeated measured from each position was deemed sufficient for the study. After sampling the ten soil cores, they were bulked to form one representative sample for each position and sent to a testing laboratory (Hills Laboratories, Hamilton; Certified NZS/ISO/IEC 17025:2005 by International Accreditation New Zealand). Samples were analysed for pH (1:2 soil to water) (Blakemore et al., 1987), Olsen-phosphorus (Olsen-P, 30-minute bicarbonate extraction followed by Molybdenum Blue Colorimetry) (Olsen et al., 1954), total nitrogen (total-N, Dumas combustion) (Nelson and Sommers, 1996), soil organic matter (Dumas combustion was used to calculate total carbon and organic matter was 1.72 x total carbon) (Nelson and Sommers, 1996), sulphate-sulphur (sulphate-S, 0.02M potassium phosphate extraction followed by Ion Chromatography) (Searle, 1988) and potassium (K, 1M neutral ammonium acetate extraction followed by ICP-OES). The two time period measurements (December 2019 and December 2021) were averaged to form one measurement per position (n = 9 per treatment).

Particle density, bulk density, pore size distribution and the water retention curve were measured between 2 cm to 5 cm in the topsoil using 3 cm (height) by 4.8 cm (diameter) cores. In each position, four replicate cores were sampled 50 cm to left of the soil moisture sensor. The measurements for each of these replicate cores were averaged per position (n = 9 per treatment). One replicate per position was used to calculate particle density (see Gradwell and Birrell (1979) for more details of the method). Particle density along with bulk density was used to calculate porosity. To calculate the water retention curve and pore size distribution, cores were equilibrated at matric potential values of -6 kPa (hanging water column) and -1500 kPa (in a pressure chamber) after being saturated. This corresponded to the pore sizes of < 54 μm and < 0.2 μm, respectively. Macroporosity was defined as pore sizes > 54 μm, and available water capacity was defined as pore sizes between 54 μm and 0.2 μm (Dörner et al., 2015; López et al., 2003b; Thomasson, 1978).

Photosynthetically active radiation (PAR) was measured 50 cm above the soil moisture sensor using a Skye PAR sensor attached to a Skye Spectro Sensor 2 data logger at each of the tree positions (Skye Instruments, UK). It was measured 30 times at solar noon, solar noon +2 hours and solar noon -2 hours on one cloudless day per season during the second year (December 2020 – December 2021). Measuring at three times during the day captured tree shading variation throughout the day. One measurement was taken in open pasture after each set of 30 measurements at a kānuka position. Light interception under the kānuka trees (LI) was each kānuka pasture PAR measurement subtracted from the paired open pasture PAR measurement. Measurements over the season and day for each position were averaged to from one LI measurement per kānuka position (n = 9 per treatment).

Precipitation (mm), wind speed (m s^{-1}), air temperature (°C) and relative humidity (%) was measured at each site using an Onset Hobo RX3000 remote monitoring station (Onset Computer Corporation, USA). For the Hawkes Bay's annual rain information, a weather station 5.8 km from the site (CliFlo, 2021) was used because the rain gauge on the monitoring station installed at the site malfunctioned.

4.2.4 Statistical analysis

A mixed effect model with treatment (kānuka and open pasture) as a fixed effect, and site as a random effect, were used to compare pasture functional groups between the treatments (Crawley, 2013; Zuur et al., 2009). The models also calculated the treatment and site interactions. Models without data transformation were visually checked to see if they followed model assumption (Crawley, 2013; Zuur et al., 2009). Because they did not, total production and all plant functional groups were square root transformed (Crawley, 2013).

Linear regression analysis was used to form the relationships between total production and the functional groups *L. perenne*, *A. capillaris,* HFA, MFS, LF and dicots. *Dactylis glomerata* was modelled using a polynomial regression analysis. The functional group LP was not modelled with total production because this group contributed little to the total production. The non-parametric spearman's rank test with a HC4 estimator was used to test correlations between species functional groups, and between species functional groups and soil variables, because this method allows for heteroscedasticity (Wilcox, 2017). The multivariate canonical variate analysis (CVA) was undertaken to discriminate which variables explained the functional group variation between the treatments and sites (Jobson, 1996; Weihs, 1995). If multiple variables are used in a CVA that respond in a similar way this can overestimate the impact of these variables in the model. This was the case for the soil physical variables, so macroporosity and available water capacity were removed from the model.

Species richness was calculated by converting pasture species percentage composition data to presence/absence data, and species richness was the total number of species in each treatment. Shannon diversity was calculated in the 'Vegan' package in the statical software R (Oksanen, 2020), and species evenness (Pielou's evenness) was calculated using (1) (Oksanen, 2020):

$$\text{Pielou's evenness} = \frac{\text{Shannon diversity}}{\log(\text{species richness})} \tag{1}$$

To account for different aspects of FD, three FD indices were calculated (functional richness (FRic), functional evenness (FEve) and functional dispersion (FDis)), using the 'FD' package in R (Laliberté and Legendre, 2010; Sonkoly et al., 2019; Villéger et al., 2008). Species traits are inputted along with the relative abundance of each species in each community (Laliberté et al., 2015). As functional groups have already been derived in the system that was studied (López et al., 2006), these functional groups were inputted as a single nominal trait. Total biomass production of each species in each community was used as the abundance data. FRic is the number of functional groups per community (Laliberté et al., 2015; Laliberté and Legendre, 2010), FEve accounts for the regularity of biomass growth for each of the functional groups in the communities (Mason et al., 2005; Tsianou and Kallimanis, 2020), and FDis is the mean distance of each functional group from a centroid calculated between the species, and thus the spread or dispersion of the community (Laliberté and Legendre, 2010). Functional divergence was not calculated as only one nominal trait was used in the analysis (Laliberté et al., 2015; Laliberté and Legendre, 2010; Mason et al., 2005). All calculated diversity indices were tested between the treatments also using mixed effect models with treatment as a fixed effect and site as a random effect. These diversity variables did not need data transformation (Crawley, 2013), and the treatment and site interactions were also calculated.

All the statistical analysis was done on R (v.4.1.1.) (R Core Team, 2021). The mixed-effect models were created using the 'lme4' package (Bates et al., 2015), the robust spearman's rank test with a

HC4 estimator was created by Wilcox (2017), and the 'candisc' package was used to do the CVA analysis and create the biplot (Friendly, 2021).

4.3 Results

There was 786 mm and 686 mm of rain in year 1 and 2 at Wairarapa, respectively, and at the weather station 5.8 km from Hawkes Bay there was 772 mm and 835 mm of rain in year 1 and 2, respectively. The average temperature in year 1 and 2 at Wairarapa was 13.2 °C (min = -0.4 °C; max = 31.8 °C) and 14.1 °C (min = 0.3 °C; max = 37.1 °C), respectively, and at Hawkes Bay it was 12.5 °C (min = -2.5 °C; max = 34.6 °C) and 13.3 °C (min = 0.8 °C; max = 30.8 °C), respectively. The average two-year windspeed was 1.3 m s^{-1} (min = 0.0 m s^{-1}; max = 16.4 m s^{-1}) and 2.5 m s^{-1} (min = 0.0 m s^{-1}; max = 16.0 m s^{-1}) at Wairarapa and Hawkes Bay, respectively. Overall, there was 67.7% and 51.5% LI under the kānuka trees at Wairarapa and Hawkes Bay, respectively. There were no correlations between light and any of the grass functional groups.

Lolium perenne then *D. glomerata* were the most abundant group in kānuka pasture, and *A. capillaris* was the most abundant group in open pasture (Table 4.2). There was significantly more total production ($p < 0.001$), *L. perenne* ($p < 0.001$), *D. glomerata* ($p < 0.01$) and HFA ($p < 0.05$) in kānuka pasture, and significantly more *A. capillaris* ($p < 0.01$), MFS ($p < 0.001$) and LF ($p < 0.001$) in open pasture (Table 4.2). Only dicots ($p < 0.05$) had a significant interaction between treatments (Figure 4.2). There was a significant relationship between total production and *L. perenne* (R^2 = 0.7, $p < 0.001$), *D. glomerata* (R^2 = 0.4, $p < 0.01$) and HFA (R^2 = 0.54, $p < 0.001$) (Figure 4.3).

Table 4.2. Total production and the production of the pasture functional groups for each treatment. All units are kg DM ha^{-1} yr^{-1}. The standard error of the mean is given in brackets.

Variable	Kānuka pasture	Open pasture	Significance
Total production	6222.8 (784.4) a	3680.6 (441.8) b	***
Lolium perenne	2560.1 (482.1) a	348.3 (96.8) b	***
Dactylis glomerata	1279.6 (238.7) a	134.0 (64.0) b	**
Agrostis capillaris	240.3 (53.5) b	716.8 (199.0) a	**
High fertility annual grasses	528.2 (236.4) a	83.5 (26.1) b	*
Medium fertility species	3.4 (2.3) b	280.5 (56.8) a	***
Low fertility tolerant grasses	0.4 (0.4) b	191.7 (51.4) a	***
Dicotyledons	89.3 (24.1) a	138.3 (36.6) a	ns
Low presence species	10.2 (6.2) a	17.0 (5.2) a	ns

Different letters represent significant differences within the sites and positions. * $p < 0.05$ level; ** $p < 0.01$ level; *** $p < 0.001$ level; ns = not significant.

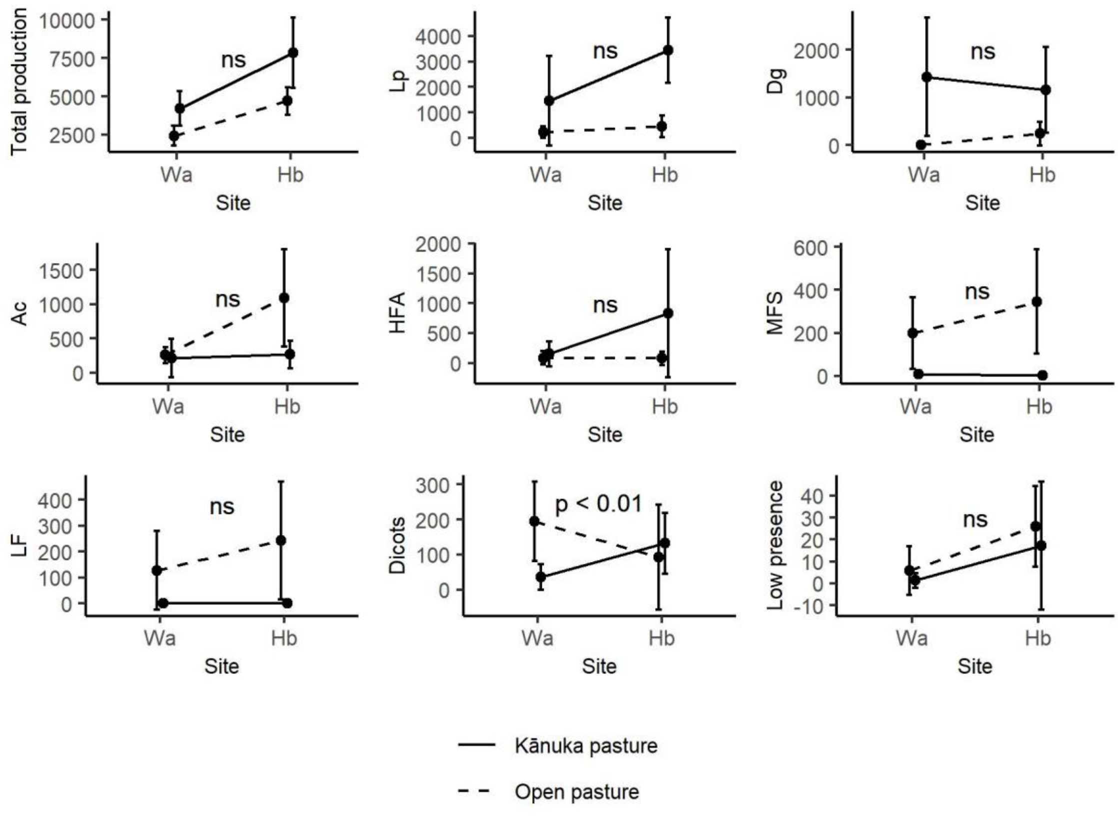

Figure 4.2. Treatment and site interactions for total production and the production of the plant functional groups. All units are kg DM ha^{-1} yr^{-1}. The shaded areas represent the 95% confidence interval. Lp = *Lolium perenne*. Dg = *Dactylis glomerata.* Ac = *Agrostis capillaris*. HFA = high fertility annual grasses. MFS = Medium fertility species. LF = low fertility grasses. Dicots = Dicotyledons.

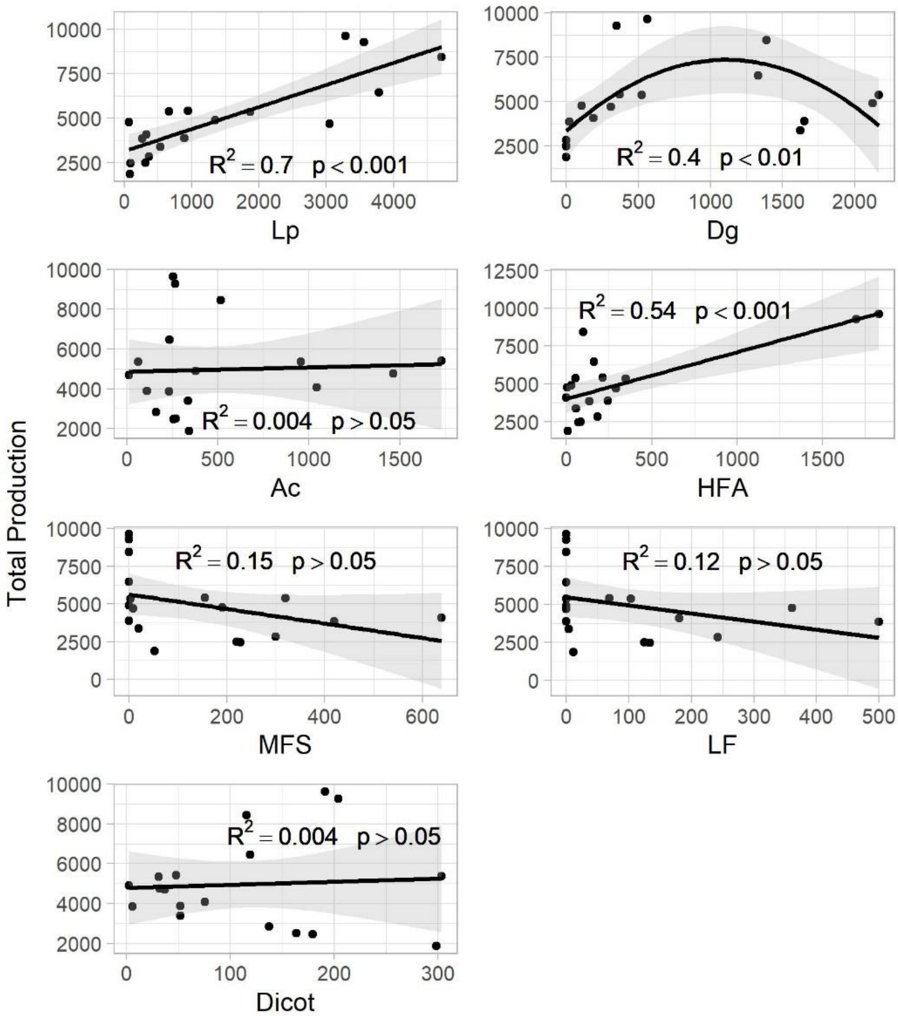

Figure 4.3. Relationships between total production and the pasture functional groups. All units are kg DM ha^{-1} yr^{-1}. The shaded areas represent the 95% confidence interval. Lp = *Lolium perenne*. Dg = *Dactylis glomerata*. Ac = *Agrostis capillaris*. HFA = high fertility annual grasses. MFS = Medium fertility species. LF = low fertility grasses. Dicots = Dicotyledons.

There was a significant correlation between total production and *L. perenne* ($p < 0.001$), *D. glomerata* ($p < 0.05$) and HFA ($p < 0.05$), and a negative correlation between total production and MFS ($p < 0.05$) and LF ($p < 0.01$) (Table 4.3). *Lolium perenne* had positive correlations with *D. glomerata* ($p < 0.01$) and HFA ($p < 0.01$), and negative correlations with MFS ($p < 0.01$) and LF species ($p < 0.01$). *Dactylis glomerata* also had negative correlations MFS ($p < 0.001$) and LF ($p < 0.001$). HFA had a positive correlation with LF ($p < 0.01$) and a negative correlation with *A. capillaris* ($p < 0.01$) and MFS ($p < 0.05$). MFS had a positive correlation with LF ($p < 0.001$).

Table 4.3. Correlations between pasture functional groups.

	TP	Dg	Ac	HFA	MFS	LF	Dicots	LP
Lp	0.80***	0.68**	-0.24 ns	0.63**	-0.75**	-0.84**	-0.01 ns	-0.26 ns
Dg	0.58*		-0.08 ns	0.27 ns	-0.67***	-0.73***	-0.37 ns	-0.31 ns
Ac	0.14 ns			-0.66**	0.24 ns	0.31 ns	0.12 ns	-0.23 ns
HFA	0.46*				-0.50*	0.72**	0.01 ns	-0.02 ns
MFS	-0.57*					0.92***	0.07 ns	0.28 ns
LF	-0.56**						0.06 ns	0.35 ns
Dicots	-0.005 ns							-0.06 ns
LP	0.31 ns							

* p < 0.05 level; ** p < 0.01 level; *** p < 0.001 level; ns = not significant. TP = total production. Lp = *Lolium perenne*. Dg = *Dactylis glomerata*. Ac = *Agrostis capillaris*. HFA = high fertility annual grasses. MFS = Medium fertility species. LF = low fertility grasses. Dicots = Dicotyledons. LP = Low presence species.

Total dry matter production was positively correlated with organic matter ($p < 0.05$), sulphate-S ($p < 0.05$), porosity ($p < 0.05$) and macroporosity ($p < 0.01$), but was a negatively correlated with VSM ($p < 0.01$) (Table 4.4; Table 4.5). *Lolium perenne* had positive correlations with Olsen-P ($p < 0.001$), organic matter ($p < 0.05$), sulphate-S ($p < 0.05$), K ($p < 0.01$) and porosity ($p < 0.001$), and MFS and LF had negative correlations with these variables. *Dactylis glomerata* had positive correlations with Olsen-P ($p < 0.01$), organic matter ($p < 0.05$), K ($p < 0.01$) and porosity ($p < 0.01$). *Agrostis capillaris* was negatively associated with Olsen-P ($p < 0.01$) and K ($p < 0.05$). HFA had positive correlations with Olsen-P ($p < 0.001$), sulphate-S ($p < 0.05$), K ($p < 0.05$) and macroporosity ($p < 0.01$).

Table 4.4. Correlations between pasture functional groups and soil fertility variables.

	Olsen-P	Organic matter	Sulphate-S	K
Total production	0.45 ns	0.56*	0.56*	0.46 ns
Lp	0.77***	0.57*	0.52*	0.68**
Dg	0.50**	0.56*	0.35 ns	0.54**
Ac	-0.58**	-0.12 ns	-0.17 ns	-0.52*
HFA	0.75***	0.36 ns	0.50*	0.60*
MFS	-0.75**	-0.64***	-0.49*	-0.71***
LF	-0.79***	-0.62**	-0.46*	-0.75***
Dicots	-0.14 ns	-0.25 ns	-0.24 ns	-0.01 ns
LP	-0.37 ns	-0.14 ns	0.05 ns	-0.39 ns

* $p < 0.05$ level; ** $p < 0.01$ level; *** $p < 0.001$ level; ns = not significant. Lp = *Lolium perenne*. Dg = *Dactylis glomerata*. Ac = *Agrostis capillaris*. HFA = high fertility annual grasses. MFS = Medium fertility species. LF = low fertility grasses. Dicots = Dicotyledons. LP = Low presence species. P = phosphorus. S = sulphur. K = potassium.

Table 4.5. Correlations between pasture functional groups and soil physical variables and volumetric soil moisture (VSM).

	Porosity	Macroporisty	Available water capacity	VSM 0–30 cm
Total production	0.53*	0.64**	0.15 ns	-0.58**
Lp	0.64***	0.03 ns	0.44 ns	-0.34 ns
Dg	0.67**	0.33 ns	0.34 ns	-0.16 ns
Ac	-0.30 ns	-0.34 ns	0.25 ns	0.6 ns
HFA	0.41 ns	0.64**	-0.30 ns	-0.45 ns
MFS	-0.72**	-0.27 ns	-0.20 ns	0.10 ns
LF	-0.75***	-0.36 ns	-0.10 ns	0.03 ns
Dicots	-0.11 ns	-0.17 ns	0.06 ns	0.09 ns
LP	-0.01 ns	0.25 ns	-0.25 ns	-0.36 ns

* $p < 0.05$ level; ** $p < 0.01$ level; *** $p < 0.001$ level; ns = not significant. Lp = *Lolium perenne*. Dg = *Dactylis glomerata*. Ac = *Agrostis capillaris*. HFA = high fertility annual grasses. MFS = Medium fertility species. LF = low fertility grasses. Dicots = Dicotyledons. LP = Low presence species. VSM = volumetric soil moisture.

4.3.1 Canonical Variate Analysis

The Canonical Variate Analysis (CVA) explained 90.4% of the total variation in pasture functional groups and soil variables in relation to the treatments (Figure 4.4). The Wilks' lambda was significant ($p < 0.05$). Canonical 1 explained 76.3% of the variation ($p < 0.05$) and Canonical 2 explained 14.1% of the variation ($p > 0.05$). Canonical 3 explained 9.6% of the variation ($p > 0.05$). Canonical variate 1 separated the data per treatment (kānuka and open pasture) (x-axis) and canonical variate 2 separated the data per site (Hawkes Bay and Wairarapa) (y-axis). The functional groups *L. perenne* and *D. glomerata*, along with Olsen-P, K and porosity, were most strongly positively associated with kānuka pasture. MFG, LF and *A. capillaris* were the groups most strongly negatively associated with open pasture.

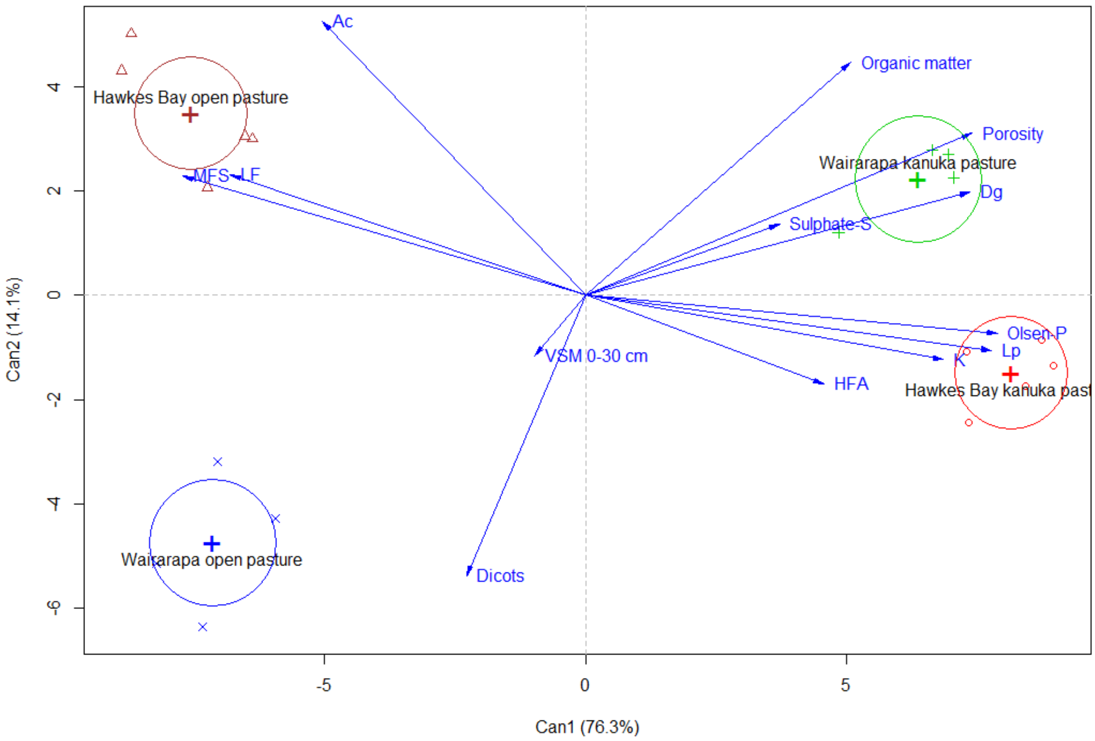

Figure 4.4. Canonical variate analysis showing which pasture functional groups and soil variables best explain treatment and site differences. Lp = *Lolium perenne*. Ac = *Agrostis capillaris*. Dg = *Dactylis glomerata*. Tr = *Trifolium repens*. HFA = high fertility annual grasses. MFS = medium fertility species. LF = low fertility tolerant grasses. Dicots = dicotyledons. LP = low presences species. P = phosphorus. S = sulphur. K = potassium. VSM = volumetric soil moisture.

4.3.2 Pasture species diversity

There was significantly lower Shannon diversity ($p < 0.01$), species richness ($p < 0.001$), species evenness ($p < 0.01$) and FRic ($p < 0.001$) in kānuka pasture (Table 4.6). There were no interactions between the treatment and site for the diversity indices (Figure 4.5). FRic was 34.8% lower than species richness in open pasture. Despite FRic and species richness both being significantly greater in open pasture, FRic was 17.7% greater in open pasture compared to kānuka pasture, and for species richness this difference was 53.4%.

Table 4.6. Shannon diversity, species richness, species evenness, functional richness (FRic), functional evenness (FEve) and functional dispersion (FDis) for the treatments. The standard error of the mean is given in brackets.

Variable	Kānuka pasture	Open pasture	Significance
Shannon diversity	1.20 (0.06) b	1.81 (1.10) a	**
Species richness	7.3 (0.23) b	11.2 (0.74) a	***
Species evenness	0.38 (0.02) b	0.58 (0.03) a	**
FRic	6.2 (0.22) b	7.3 (0.24) a	***
FEve	0.39 (0.05) a	0.45 (0.04) a	ns
FDis	0.26 (0.01) a	0.30 (0.01) a	ns

Different letters represent significant differences within the sites and positions. ** $p < 0.01$ level; *** $p < 0.001$ level; ns = not significant.

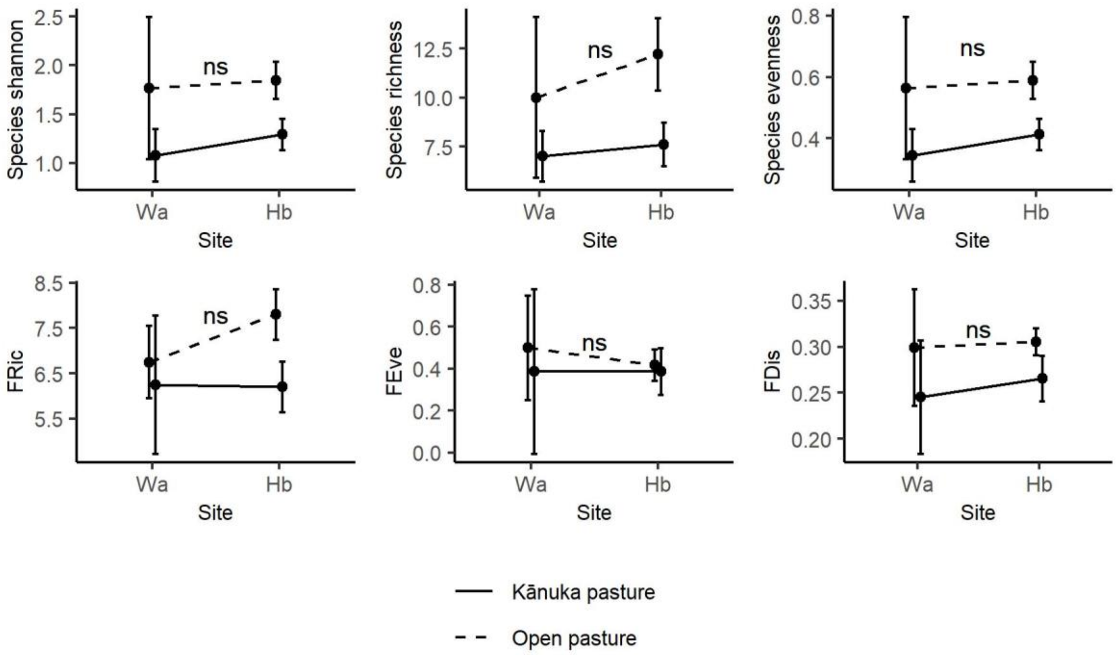

Figure 4.5. Treatment and site interactions between the diversity indices. The error bars are the 95% confidence intervals. Wa = Wairarapa. Hb = Hawkes Bay. FRic = Functional richness, functional evenness. FEve = functional evenness. FDis = functional dispersion.

4.4 Discussion

4.4.1 Functional groups and pasture production outcomes

The significantly greater total pasture production in kānuka pasture was associated with increased levels of soil fertility in terms of organic matter, sulphate-S, soil organic matter, as well as increased porosity and macroporosity. Mackay-Smith et al. (2022) concluded that these conditions in the kānuka pasture environment were most likely because of nutrient transfer and organic matter addition by livestock from the open pasture environment to the kānuka pasture environment, and organic matter addition to the soil by trees. This study shows that these conditions in kānuka pasture are associated with a complete change in the pasture functional group composition between the kānuka and open pasture environment. *Dactylis glomerata*, *L. perenne* and HFA were the functional groups associated with the improved soil conditions, and these species were most strongly positively associated with Olsen-P, K and porosity (Figure 4.4).

Poorer condition environments with less resources often select for 'slow trait' plants, which grow slower and have resource conservation strategies, whereas environments with more abundant resources often have faster growing plants that have traits that can better utilise resources (Buckland and Grime, 2000; Reich, 2014; Rice and Nagy, 2000). These faster growing species can be defined as competitor species, and these competitor species can outcompete 'slow trait' plants (Buckland and Grime, 2000; Gurevitch and Unnasch, 1989; Marañon, 1986). These competitor species are the mechanism for the mass effect hypothesis, with a few dominant species being the principal contributors to the total biomass growth of a community (Abul-Fatuh and Bazzaz, 1979; Grime, 1998; Sonkoly et al., 2019). This study also found evidence of the mass effect hypothesis, with total production being associated with the growth of *L. perenne*, *D. glomerata* and HFA (Table 4.2; Figure 4.3).

This study shows that when silvopastoral trees increase the availability of nutrients and improve soil structure, the growth of competitor species such as *D. glomerata* and *L. perenne* can result in more pasture production under silvopastoral trees. Marañon (1986) also found the percentage cover of *D. glomerata* increased under oak (*Quercus* spp.) trees in a Spanish *dehesa* site, suggested to be because of increased soil nitrogen or increased VSM availability (Joffre and Rambal, 1988; Marañon, 1986; Marañón and Bartolome, 1994). The consistent findings of silvopastoral trees having the potential to increase the growth of competitor and more productive pasture species in this present study and Marañon (1986) indicates that trees could be an important management option to farmers for improving the production of diverse pastures because of their positive influence on fast growing and competitive functional groups. This could be especially important in New Zealand hill country, because even though open pasture at both sites had a history of annual fertilisation, *A. capillaris* and MFS mainly grew in open pasture.

The species composition under the trees in the present study was similar to productive low slope (< 13°) microsites studied by López et al. (2006). Nevertheless, the positions in this study were between 20° and 25°, and in López et al. (2006)'s medium slope class (13–25°), *A. capillaris* and MFS had 53% and 23% of the total percentage composition of green dry matter production, respectively, and *L. perenne* and high fertility grasses had 3% and 7%, respectively. It was only in low slope microsites that *L. perenne* (45%) and high fertility grasses (21%) had a greater proportion of green dry matter production. This suggests that silvopastoral trees can change the pasture functional groups that grow on medium sloped classes in New Zealand hill country so they are similar to the lower sloped classes reported by López et al. (2006).

The findings of this study, however, contrast with other studies that have measured the biomass growth of individual pasture species in silvopastoral systems (Douglas et al., 2006; Guevara-Escobar et al., 2007; Marañón and Bartolome, 1994). LI by the trees studied by Marañón and Bartolome (1994) was 97.7%, which was reported to be why pasture production was diminished under the trees that they studied. This present study shows that it is important silvopastoral trees have at least a LI of 65% to promote the growth of more productive functional groups. Guevara-

Escobar et al. (2007) and Douglas et al. (2006) also studied pastures in a New Zealand silvopastoral system with poplar. Both studies found significantly less pasture production under the trees but did not find noticeable differences in pasture composition between tree and open pasture. This was most likely because of the contrasting bio-physical tree attributes of poplar compared to kānuka (Mackay-Smith et al., 2021), and how these attributes interact with pasture production.

4.4.2 ***Individual species interactions***

In past New Zealand silvopastoral research when comparing tree-pasture environments with open pasture, the percentage composition of *L. perenne* has been shown to only decrease under radiata pine (*Pinus radiata* D. Don) (Cossens and Hawke, 2000; Hawke, 1991; Percival and Hawke, 1985) and be similar (Douglas et al., 2006; Wall, 2006) or decrease (Crowe and McAdam, 1992; Guevara-Escobar et al., 2007) under poplar. The results of this study show that soil conditions can improve under some silvopastoral trees in New Zealand and lead to an increase in the production of *L. perenne* when compared to open pasture.

However*, L. perenne* was not dominant in all kānuka pasture positions, and *D. glomerata, B. hordeaceus* and *C. murinum* were also abundant in kānuka pasture. In hill country without trees, López et al. (2006) reported low amounts of *D. glomerata*, even in high fertility microsites. Nevertheless, other hill country studies that have studied pasture under trees in hill country have recorded *D. glomerata* (Cossens and Hawke, 2000; Douglas et al., 2006)*.* Previous research indicates the potential of *D. glomerata* as a viable silvopastoral pasture species because of its tolerance to shade (Joshi, 2000; Koukoura and Kyriazopoulos, 2007; Kyriazopoulos et al., 2013; Mosquera-Losada et al., 2006; Peri et al., 2001a, 2001b). In New Zealand hill country, despite finding 22% less overall grass production under poplars, Douglas et al. (2006) found more *D. glomerata* under the trees compared to open pasture, which reinforces its capability to grow in shade conditions. This present study gives further evidence of this.

Despite *D. glomerata* being competitor species (Buckland and Grime, 2000; Gurevitch and Unnasch, 1989), the relationship with total production was unimodal (Figure 4.3). This reveals that *L. perenne* and *D. glomerata* function differently in the agroecological system and have distinctive functional strategies. This unimodal relationship could have been because of the mixed strategy functions of *D. glomerata*. In addition to its function as a competitor species, *D. glomerata* has been shown to have stress tolerator traits (in terms of light and water stress) (Devkota et al., 2009; Lin et al., 1999; Turner et al., 2012; Van Sambeek et al., 2007). For example, when comparing two *D. glomerata* cultivars and a *L. perenne* cultivar, Lin et al. (1999) found *D. glomerata* had significantly more growth in 50% and 80% shade in spring and early summer. Moreover, *L. perenne* has been shown to have reduced leaf dry matter growth, more daughter tiller deaths and reduced water-soluble carbohydrate reserves compared to *D. glomerata* in drought conditions. (Turner et al., 2012). These reasons indicate the relevant function of *D. glomerata* in maintaining pasture production in the tree-pasture environment when *L. perenne* survival and persistence is compromised.

The other two abundant species in the kānuka pasture positions were the annuals *C. murinum* and *B. hordeaceus*, although the abundance of both these species was much less than *D. glomerata* and *L. perenne* (Table 4.2). Both *C. murinum* and *B. hordeaceus* grow in nutrient rich areas (Cocks, 1974; Groves et al., 2003; Škornik et al., 2010), and *C. murinum* has been shown to compete with *L. perenne* and *D. glomerata* at high soil fertility levels (Groves et al., 2003). In this present study, the two positions with the greatest production overall also had the greatest production of high fertility annuals. Therefore, the growth of these annuals is a valuable support for maintaining pasture feed during spring.

Neither *C. murinum* nor *B. hordeaceus* were recorded by López et al. (2006). This was probably because the long-term rainfall averages at both sites in this present study (Wairarapa: 903 mm; Hawkes Bay: 889 mm) was lower than the rainfall at López et al. (2006)'s site (1270 mm). *Critesion* *murinum* also grows in drier regions such as Mediterranean-style dry pastoral systems with ~400 mm of rain (Chano et al., 2021), and in semiarid regions of low rainfall (200– 350 mm per year) in Jordan (El-Shatnawi et al., 1999). *Bromus hordeaceus* also grows with *C. murinum* in the South of France (Delpuech and Metay, 2018) and is an important pasture species in California (Jackson, 1985). Perennial species, such as *L. perenne* and *A. capillaris*, may have outcompeted these annuals in López et al. (2006)'s study because rainfall was less limiting. Therefore, annuals species, such as *C. murinum* and *B. hordeaceus*, may have a space and function in more water shortage stressed pastoral ecosystems and occupy a niche, contributing to the production and sustainability of drier silvopastures in New Zealand.

A negative aspect of *C. murinum* is that their seed heads can penetrate sheep wool and skin, impacting sheep growth and their wool (Bourdôt et al., 2007; Ghanizadeh and Harrington, 2019). Because of this, it has also been identified as one of the most important agricultural weeds by farmers in a survey in New Zealand (Bourdôt et al., 2007). The potential benefits to production from the growth of *C. murinum* must be considered against this cost.

All species of clover measured in this study had low presence. Past studies have found *T. repens* to be impacted by artificial shade (Ehret et al., 2015; Wachendorf et al., 2001) and silvopastoral tree shade (López-Sánchez et al., 2016). Ehret et al. (2015) found 93% reductions of *T. repens* in 80% shade and Wachendorf et al. (2001) found *T. repens* to be strongly negatively impacted by temperature and radiation. Therefore, despite improved soil fertility, this study gives more evidence that clover is negatively impacted by silvopastoral trees. Additionally, clover was also most likely limited by the reduced levels of S and K in open pasture, with both these nutrients negatively associated with the functional groups that grew in open pasture (Table 4.4).

López et al. (2006) found *A. capillaris* in similarly high amounts in various fertility/stocking rate and slope treatments and concluded that *A. capillaris* was highly plastic to the changing hill country environmental conditions. This finding was also found at the Wairarapa site in this study, with similar amounts of *A. capillaris* in kānuka and open pasture, but not at Hawkes Bay, with there being more *A. capillaris* growth in open pasture at Hawkes Bay compared to Wairarapa. Because the soil type, aspect, slope gradient and rainfall were similar between sites, the increased growth of *A. capillaris* in Hawkes Bay is indicative of improved soil fertility in open pasture at Hawkes Bay. This increased growth of *A. capillaris* in open pasture at Hawkes Bay, but the lack of growth of the competitors *D. glomerata* and *L. perenne* in these positions, gives evidence that *A. capillaris* has its own competitive niche between where *D. glomerata* and *L. perenne* grow and MFS and LF species grow. Moreover, *A. capillaris* still has stress tolerator traits because it persisted in poorer soil conditions where *L. perenne* could not. This gives evidence that *A. capillaris* can be considered as a step between poorer quality-productive pasture dominated by medium and low fertility species, and higher quality-productive pasture dominated by *L. perenne* and other high fertility species.

The low fertility species in this present study responded in a similar way to the species studied by López et al. (2006) and Nicholas (1999), and had almost no production in better soil conditions, but were able to persist in the poorer soil conditions of open pasture. This indicates that these species are stress tolerators (Grime et al., 1988; Reich, 2014). The growth of these species in poorer soil conditions are still important for maintaining a good pasture cover in open pasture areas, which has been shown to reduce surface runoff and associated sediment losses compared to higher fertility areas under kānuka trees that are grazed more frequently (Mackay-Smith et al., 2022).

4.4.3 Pasture diversity and stability

Other past studies in oak silvopastoral systems in southern Europe have also found reduced pasture diversity under trees in presence/absence and percentage cover studies (Fernández-Moya et al., 2011; López-Carrasco et al., 2015; Marañon, 1986; Rossetti et al., 2015). This study also found that the increased growth of more competitor species in kānuka pasture, such as *L. perenne*, *D. glomerata* and HFA, were related to reduced Shannan diversity, species richness, species evenness and FRic (Table 4.6). The loss of species and functional richness in this present study and past studies could have impacted pasture stability, with previous studies finding relationships between increasing species richness and increasing pasture stability (Frank and McNaughton, 1991; Tilman and Downing, 1994). Nevertheless, studies have also found that low species diversity communities can be as stable as high species diversity communities, and that the presence of a low number of stress tolerator species is more important than overall species diversity (Sankaran and McNaughton, 1999; Tracy and Sanderson, 2004).

FEve and FDis were, however, similar between kānuka pasture and open pasture. This shows that despite reduced species richness, species evenness and FRic in kānuka pasture, the silvopastoral environment maintained a similar growth evenness and spread of different functional groups throughout the year compared to open pasture. As was explained in the previous section, the functional groups that were promoted in kānuka pasture had different survival strategies, with *D. glomerata* and *A. capillaris* having stress tolerant traits, and the HFAs not persisting through summer. These results give evidence that the kānuka trees maintained pasture stability because they promoted the growth of a range of functional groups with specific stress tolerant traits.

Although FRic was significantly less in kānuka pasture, there was a 53.4% greater species richness in open pasture compared to kānuka pasture for species richness, but this increase was only 17.7% for FRic. Moreover, the statistically different species evenness between kānuka and open pasture, but the statistically similar FEve and FDis between kānuka and open pasture, highlights that species diversity indices overestimated diversity reductions in kānuka pasture. This shows it is very important to consider FD in future silvopastoral research to appropriately assess the impact diversity changes to system functioning.

Past studies have shown that species richness (Roscher et al., 2007; Weigelt et al., 2009) and FRic (Hector et al., 1999) positively impact productivity. This has been hypothesized to be because of complimentary effects between species (Marquard et al., 2009; Weigelt et al., 2009) and sampling effect (increasing the chance of higher producing species in the community) (Aarssen, 1997; Huston, 1997; Marquard et al., 2009; Tilman et al., 1997). Nevertheless, this study found less species richness and FRic in positions with more production. This gives further evidence of the mass ratio hypothesis, and that the presence of more productive individuals drives biomass productivity, and productivity is less sensitive to species richness changes in silvopastoral systems (Grime, 1998).

Despite these positive results, as this is the first study to measure the impact of a kānuka silvopastoral system on pasture functionality in New Zealand hill country, more research is required to validate these findings in different climates, aspects, soil types, topographies and management types. Moreover, livestock camping spots were specifically avoided during site selection. Further research is required to understand the dynamics of livestock camping in hill country and mitigation options to form more generalised conclusions as to how kānuka impacts pasture functionality at farm scale. Nevertheless, these initial results are highly encouraging, and show that a kānuka silvopastoral system has potential for positively influencing hill country grazing systems.

4.5 Conclusion

This study investigated pasture production and pasture stability outcomes in silvopastoral systems from a functional ecology perspective, and compared pasture functional group production and FD under and away from kānuka trees in New Zealand hill country. This study highlights the potential of silvopastoralism to increase pasture production by increasing the growth of fast-growing and competitive species, with *L. perenne*, *D. glomerata* and HFA (*B. hordeaceus* and *C.*

murinum) having greater biomass in the kānuka environment because of improved soil fertility (Olsen-P and K) and porosity. The production of medium fertility and low fertility grasses were greater away from the trees in poorer soil conditions and were associated with increasing species diversity.

Despite reduced species diversity and FRic in kānuka pasture, FEve and FDis was similar between kānuka pasture and open pasture positions. Additionally, because functional groups were promoted in kānuka pasture that had a range of survival strategies, such as those with mixed (*D. glomerata* with stress tolerant traits) and annual survival strategies (*B. hordeaceus* and *C. murinum*), this is evidence that pasture stability was maintained in kānuka pasture. Furthermore, Shannon diversity, species richness and species evenness overestimated diversity reductions compared to FD, so considering functional indices is integral for appropriately measuring how diversity impacts pasture production and stability outcomes in silvopastoral systems. Because of these impacts to production and stability outcomes, silvopastoral systems may have great potential for sustainably improving diverse pastoral systems.

Chapter 4 summary

Using a functional ecology perspective, this chapter explored hypothesis 2 by measuring the ecological mechanisms for how a kānuka silvopastoral system impacts pasture production and pasture stability. This study highlighted the potential of silvopastoralism to increase pasture production by increasing the growth of fast-growing and competitive species, with *L. perenne*, *D. glomerata* and HFA (*B. hordeaceus* and *C. murinum*) having greater biomass in the kānuka environment because of improved soil fertility (Olsen-P and K) and porosity. Nevertheless, these are preliminary findings and more research is required to confirm these results on other farms and in other hill country situations.

Chapter 5 The impact of a kānuka silvopastoral system on surface runoff and sediment and nutrient losses in New Zealand hill country

This chapter explores hypothesis 3 and measures the impact of a kānuka silvopastoral system on one of the most important current environmental challenges in New Zealand hill country: surface runoff and sediment and nutrient losses.

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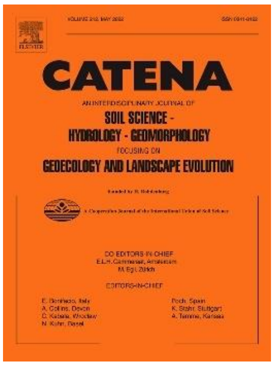

5.1 Introduction

New Zealand hill country is an agricultural area with steep or hilly land (> 15°), an altitude < 1000 m asl and has pastoral farming as its main land use (sheep, cattle and deer) (Dodd et al., 2016). Hill country in New Zealand is susceptible to surface runoff and sediment and nutrient losses due to the wide extent of agriculture on the land (Basher et al., 2008; Mackay, 2008), and its topography, lack of woody vegetation, weak rock and poor soil conditions (Basher, 2013; Hicks et al., 2011; Kemp and López, 2016). McDowell and Wilcock (2008) reviewed average sediment and nutrient losses in surface runoff in sheep and cattle grazed New Zealand catchments (predominantly hill country catchments), and found there to be average losses of 11 kg ha^{-1} yr^{-1} for total-nitrogen (total-N), 1.3 kg ha^{-1} yr^{-1} for total-phosphorus (total-P) and 1156 kg ha^{-1} yr^{-1} for suspended sediment. McDowell et al. (2017) estimated 77% of the mean national loads of sediment, N, P and *Escherichia coli* to be from low-order streams (the majority of which are in hill country).

Increased sediment loads in waterways has been shown to alter river ecosystems (Davies-Colley and Smith, 2001; Ryan, 1991) and negatively impact river biota (Matthaei et al., 2006). Economic costs from soil erosion and waterway sedimentation in New Zealand can exceed $150 million NZD annually (Krausse et al., 2001). Nutrient losses into surrounding streams from agricultural catchments can be over 10% of yearly fertiliser inputs (McDowell and Wilcock, 2008), and can negatively impact water bodies by promoting excessive algal growth (Bunting et al., 2007; Hecky and Kilham, 1988).

In addition to sediment and nutrient losses, downstream rivers in New Zealand can be highly susceptible to impactful flooding (Fuller and Heerdegen, 2005; Jowett and Richardson, 1989; Paulik et al., 2021), resulting in social (Smith et al., 2011), environmental (Fuller and Heerdegen, 2005) and economic costs (Walton et al., 2004). The Manawatū River in the North Island of New Zealand experienced a destructive 100-year flood in 2004 with hill country contributing a large part of its catchment (Fuller, 2008). As far as we are aware, no study has quantified how much flood water in New Zealand is as a result of forest clearing in hill country, but losses from hill country pastures can be significant (Bretherton et al., 2018; Gillingham and Gray, 2006; Lambert et al., 1985). For instance, Bretherton et al. (2018) studied repellency-induced runoff in 2 m^2 plots and during these events runoff ranged from 1% to 59% of rainfall. Gillingham and Gray (2006) found surface runoff to be 18% to 26% of total rainfall in two hill country pastoral catchments (12.6 ha and 12.8 ha in area). Strategies that reduce surface runoff and enhance rainfall infiltration into hill country soils will be critical to reduce the risk of flooding.

Forested hill country catchments have been shown to reduce losses compared to paired pasture catchments (Bargh, 1978; Cooper and Thomsen, 1988; Marden et al., 2014; Quinn and Stroud, 2002). For example, sediment load reductions following radiata pine (*Pinus radiata* D. Don) reforestation of a hill country catchment were studied by Marden et al. (2014) over a 50-year period. Following reforestation, erosion rates were estimated to reduce by ~51%, which represented an estimated sediment yield reduction of ~12%. Bargh (1978, 1977) studied streamflow, suspended sediment, total-N and total-P outputs from a 10 ha native forested catchment and a 180 ha agricultural catchment that were ~8 km apart on similar soil types and topographies. Streamflow discharge as a proportion of total rainfall was approximately ~12% less in the forested catchment. Suspended sediment, total-N and total-P outputs in the forested catchment were 120 kg ha^{-1}, 0.2 kg ha^{-1} and 2.0 kg ha^{-1}, and 1400 kg ha^{-1}, 1.6 kg ha^{-1} and 5.2 kg ha^{-1} in the paired agricultural catchment, respectively.

Although forests ('natural' and planted) are effective at reducing surface runoff and sediment and nutrient losses, it does not allow for pastoral agriculture due to the densely spaced trees and the lack of sunlight for pasture growth. An alternative on-farm vegetation mitigation option for reducing surface runoff and sediment and nutrient losses is agroforestry. We define agroforestry as there being at least two plant species that interact biologically, where at least one of the plant species is a woody perennial (typically trees), and at least one of the plant species is managed for forage, annual or perennial crop production (Somarriba, 1992). Zhu et al. (2020) compiled data from 83 case studies and 33 countries that measured the influence of agroforestry on water, sediment and nutrient losses. On average, these agroforestry systems reduced water loss by 58% (range: 1–100%), soil loss by 56% (range: 0–97%) and related nutrients by 50% (range: -265–100%).

Silvopastures were one type of agroforestry system reviewed by Zhu et al. (2020), and these are agroforestry trees growing in pastoral land (Nair, 1993). Their influence on agricultural losses have been well studied (Bambo et al., 2009; de Aguiar et al., 2010; Grewal et al., 1994; Hussain, 2009; López-Díaz et al., 2011; Michel et al., 2007; Nair et al., 2007), but there remains a fundamental research gap. As far as we are aware, no studies have measured surface runoff and associated sediment and nutrient losses from paired areas of permanent pasture with and without fully-grown silvopastoral trees. The only way to assess if silvopastoral systems are a mitigation option for reducing surface runoff and sediment and nutrient losses in agricultural systems is to compare these losses in a silvopastoral system with paired areas of open pasture. None of the silvopastoral studies reviewed by Zhu et al. (2020) compare *measured* surface runoff and associated sediment and nutrient losses between permanent pasture and a silvopastoral system. Hussain (2009) has compared surface runoff and sediment and nutrient losses between open pasture and a 4-year-old 1.2 m by 1.2 m *Populus* spp. silvopastoral system in New Zealand, however, this density is too high for a viable silvopastoral system with good grass cover when these trees are fully-grown (Wall et al., 2006).

If silvopastoral trees can be found to improve soil structure, this may result in more water infiltrated into the soil (McLaren and Cameron, 1996), reducing the amount of surface runoff and associated sediment and nutrient loads in pastoral areas. Increased soil porosity will extend the time until soil saturation, again reducing the amount of surface runoff and decreasing the chance of slope failure (Young, 1989). If organic matter increases under the trees, soils become more stable (Ekwue, 1990; Guerra, 1994; Morgan, 2005), and less sediment and nutrients may be lost. The root system of the trees will take up soil nutrients, which has been shown to reduce nutrient leaching (Bambo et al., 2009). Surface runoff will also be influenced by livestock grazing frequency and intensity that impact vegetation under the tree canopy compared to open pasture (Chen et al., 2018; El Kateb et al., 2013). These reasons mean that the integration of a silvopastoral system into hill country could substantially reduce surface runoff and associated sediment and nutrient losses.

This paper studies a kānuka (*Kunzea* spp.) hill country silvopastoral system. Kānuka is a native, successional and evergreen tree genus with 10 endemic New Zealand species (de Lange, 2014), which is common in New Zealand hill country (Bergin et al., 1993; Spiekermann et al., 2021). Kānuka has potential as a silvopastoral genus due to its many beneficial tree attributes, such as its height, adaption to local conditions and evergreen nature (Mackay-Smith et al., 2021). A kānuka silvopastoral system has received little research attention, with previous research studying its landslide mitigation effectiveness at the landscape scale (Bergin et al., 1993; Spiekermann et al., 2021). There have been no published studies examining the interaction of kānuka as a silvopastoral tree in hill country at the field scale (Mackay-Smith et al., 2021). The study objectives are to 1) measure and contrast surface runoff and associated sediment and nutrient losses (nitrogen and phosphorus) between a New Zealand hill country kānuka silvopastoral system and a hill country pastoral system without trees, and 2) identify the reasons for surface runoff and sediment and nutrient loss differences between the treatments.

5.2 Methods

5.2.1 Study area

This study was undertaken in the North Island of New Zealand, in the Wairarapa region, ~10 km north of Martinborough (41° 08.42′ S, 175° 29.58′ E, elevation 122 m) (Figure 5.1A; Figure 5.1B).

The region has a temperate climate and the 30-year (1991–2020) mean annual rainfall is 903 mm (min: 545 mm; max: 1297 mm) (the Downs weather station (2631); 6.7 km from the site; elevation 61 m) (CliFlo, 2021). The 10-year (2011–2020) mean annual maximum daily temperature from the same climate station is 18.3 °C, with a mean summer and winter maximum daily temperature of 23.3 °C and 14.0 °C, respectively (CliFlo, 2021). Soil at the site is a Mottled Argillic Pallic soil in the New Zealand classification and a Ustalf in the USA classification (Hewitt, 2010), with a topsoil that is a dark-greyish silty loam overlaying a pale-brown silty clay loam and a pale-brown light-yellowish brown grey silty clay loam. The soil overlays partly iron-stained greywacke and argillite that are both sedimentary rocks. Greywacke is one of the most extensive basement rocks in New Zealand and is the predominant rock in the central mountain ranges of the North and South Island (Thornton, 2009). The topography of the site is moderately to severely steep, and the average slope gradient of the study area is 25.9°.

The site is on a commercial sheep and beef farm and is in permanent, naturalised pasture. Hill country pastures vary depending on environmental conditions (López et al., 2006), however, the two predominant pasture species in New Zealand hill country are normally browntop (*Agrostis capillaris* L.) and perennial ryegrass (*Lolium perenne* L.) (López et al., 2006; Nicholas, 1999). Individual *Kunzea robusta* de Lange et Toelken trees (kānuka, the common name for the genus *Kunzea* will be used), grow scattered across the site (Figure 5.2C). Many of the trees are fully-grown and tree densities range from 10 trees ha^{-1} to 2000 trees ha^{-1}. Old aerial imagery shows that the fully-grown kānuka trees examined in this study are at least 80 years old (Retrolens, 2021). The trees most likely established via seed after the land was cleared for grazing.

The paddock has an effective grazing size of 3.5 ha (there is 0.7 ha of closed canopy forest in the paddock). It is rotationally grazed for two days to three days throughout the year by ewes at a grazing intensity of 57 ewes ha^{-1} day^{-1}, lambs at 40 lambs ha^{-1} day^{-1}, Angus cows at 9.1 cows ha^{-1} day^{-1} and Friesian bulls at 3.4 bulls ha^{-1} day^{-1}. The site has been fertilised with 21.5 kg P ha^{1} and

37 kg S ha^{1} that is surface applied as a granular single superphosphate and super sulphur (S) 15 mixture annually in early summer.

5.2.2 Study design and measurements

5.2.2.1 *Runoff plots*

The study ran for one year from 20th May 2020 to 19th May 2021. Six runoff plots were established in the same paddock, all with a consistent slope position (shoulder of the slope), slope gradient (24–28°) and aspect (north facing) (Figure 5.2C). The plots ranged from 32–39 m^{2} (~4.5 m x ~8.0 m) (size varied due to difficulties in positioning the gutters that collected surface runoff on the slopes due to difficult terrain). Sediment and nutrient loads accounted for this plot size variation as they were calculated on an area basis. Three plots had individually-spaced kānuka trees growing with pasture underneath ('kānuka pasture') (plots 1–3), and three had no trees growing in them ('open pasture') (plots 4–6) (Figure 1C). Two of the kānuka plots had three individual kānuka trees and the other kānuka plot had two individual kānuka trees. There was no noticeable channelised flow in the plots. Shade fell on all three open pasture plots from nearby trees after ~16:00 until sunset. The eight trees in the kānuka pasture plots result in a density of ~750 trees ha^{-1} when calculating density as the number of stems per the area of the kānuka plots. But if density is calculated with the study area (open and kānuka pasture plots) in the centre of a 50 x 50 m square, the tree density is 68 trees ha^{-1}. In terms of the number of stems within the plots, the density of the kānuka plots was relatively high as multiple stems were growing close together (Figure 5.2A), however, plenty of light still reached the plots as the density around the plots was low.

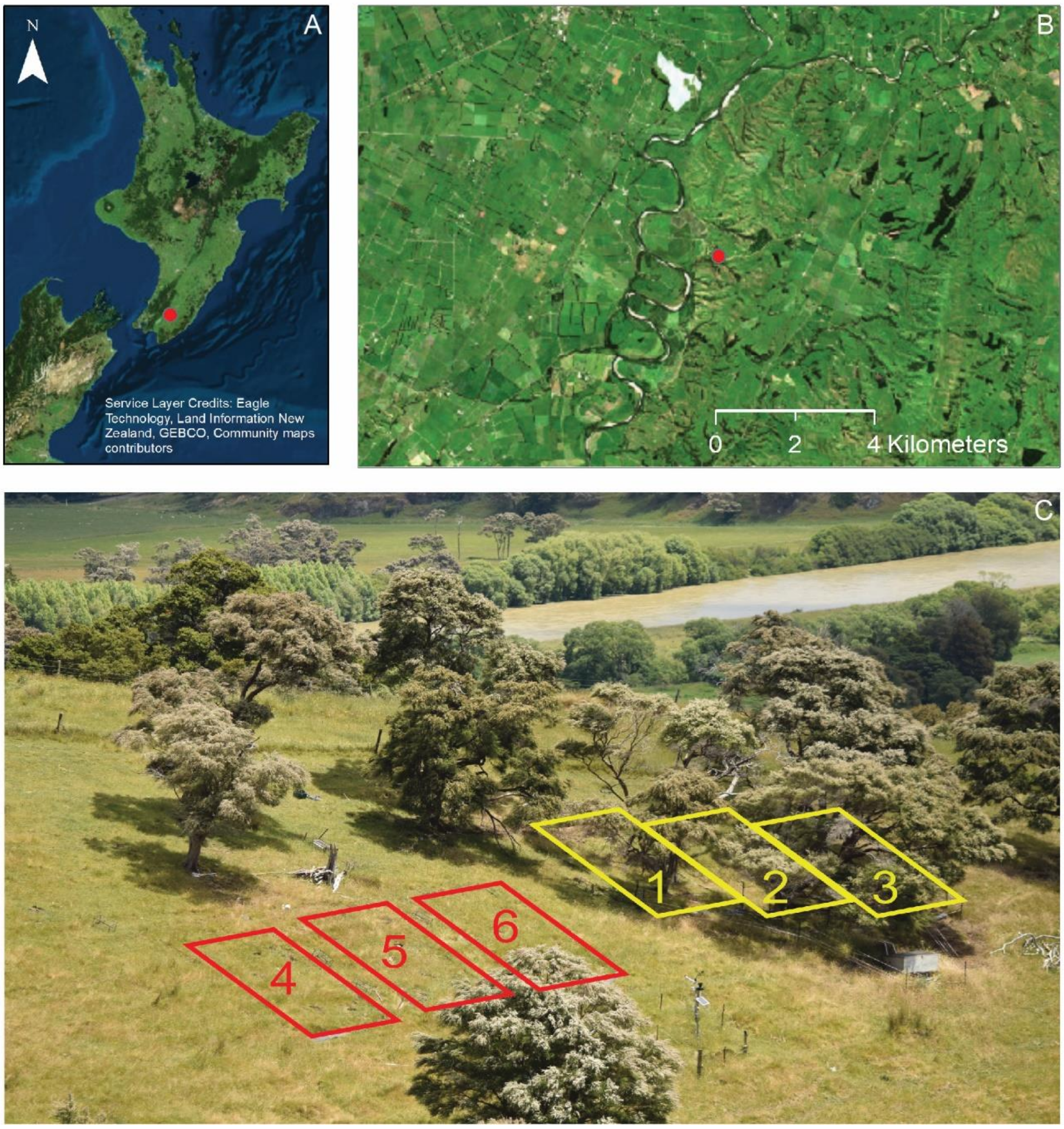

Figure 5.1. Study site and plot locations. A: The location of the study site in relation to the North Island of New Zealand (red dot). B: Location of the study site in relation to the local region (red dot). The Ruamahanga River runs directly down the imagery to the west of the site. C: Location of the six plots, the kānuka pasture plots are in yellow, and the open pasture plots are in red. Figures A and B are from the same satellite imagery layer and the photograph in C was taken by the lead author.

Black plastic edging was pushed ~10 cm into the soil on the plot boundaries to hydrologically isolate each plot (Figure 5.2A). A 15 cm open channel was dug along the top boundary of each plot to divert any surface run-on and to ensure that only surface runoff generated from within the plot was collected. White plastic gutters were secured at the bottom of each plot and covered with black plastic edging to prevent rainfall entering (Figure 5.2B). These gutters directed runoff to calibrated tipping buckets housed in a shelter and there was one tipping bucket per plot (Figure 5.2C). Tipping bucket volumes ranged from 2.45–2.70 L. *In situ* manual counters recorded the number of tips. The tipping buckets were also connected to Onset HOBO S-UCD-M001 2Hz contact closure sensors that logged tips via a telemetered Onset HOBO RX3000 remote monitoring station (Onset Computer Corporation, USA). This was back-up in case of any manual counter failures as well as a notification for when a surface runoff event had taken place. A tip occurred after ~0.07 mm of surface runoff (this varied due to slight differences in the size of each plot and individual tipping buckets). A small subsample of runoff was collected after each tip and transferred to a plastic container which generated a single representative water sample from each plot, for each event, for nutrient and sediment analysis.

5.2.2.2 *Surface runoff sampling and analysis*

A surface runoff generating event was defined as when any amount of water was collected in at least one of the tipping buckets. Following a surface runoff generating event, the number of tips were recorded from the manual counter. If a tipping bucket was not completely full, the volume of water was recorded to the accuracy of 0.25 of a bucket. Samples were either taken from the plastic container or the tipping bucket (if there was not enough sample in the plastic container) and were stirred before sampling to ensure that different sediment particles sizes were mixed within the sample.

Samples were kept cool and couriered to the testing laboratory (Hills Laboratories, Hamilton, New Zealand; Certified NZS/ISO/IEC 17025:2005 by International Accreditation New Zealand) immediately after sampling where they were analysed within 48 hours of collection. Nitrate-N, ammonium-N and dissolved reactive phosphorus (DRP) were filtered to < 0.45 μm on arrival at the laboratory. Sample concentrations were analysed for Total Kjeldahl Nitrogen (TKN) via Total Kjeldahl digestion, phenol/hypochlorite colorimetry and discrete analysis (APHA 4500-N_{org} D (modified), and 4500 NH_3 F (modified) 2017, 23rd edition), nitrite-N via automated azo dye colorimetry and flow injection analysis (APHA 4500-NO_3^- I (modified), 2017, 23rd edition), nitrate-N + nitrite-N via total oxidised nitrogen, automated cadmium reduction and flow injection analysis (APHA 4500-NO_3^- I (modified) 2017, 23rd edition), ammonium-N via phenol/hypochlorite colorimetry and flow injection analysis (APHA 4500-NH_3 H (modified), 2017, 23rd edition), total-P via total phosphorus digestion, automated ascorbic acid colorimetry and flow injection analysis (APHA 4500-P B&E, 2017, 23rd edition) and DRP via molybdenum blue colourimetry and flow injection analysis (APHA 4500-P G (modified) 2017, 23rd edition). Total-N was the sum of TKN, nitrate-N and nitrite-N. Nitrate-N was the nitrate-N + nitrite-N value minus nitrite-N. Suspended sediment was measured by filtering ~1 L of sample through a GF/C grade filter paper, which was dried and weighed to calculate suspended sediment concentration.

Surface runoff amount (mm) was calculated by multiplying the number of tips by the volume of each tipping bucket (L), then dividing this by the plot size (m^2). Sediment and nutrient loads (kg ha^{-1}) were calculated by multiplying measured concentrations (g m^{-3}) by the volume of surface runoff (m^3) and dividing this by the size of each plot. After sampling, each tipping bucket and container was cleaned using water and a brush, and the counter reset.

Figure 5.2. Surface runoff plot equipment. A: The kānuka pasture treatment plot 1–3 (the photograph was taken in early Spring). B: An open pasture plot (plot 5) and surface runoff collecting gutters covered by plastic edging (the photograph was taken in late summer, the pasture under kānuka became a similar colour in late summer). C: Tipping buckets collecting surface runoff. All photographs were taken by the lead author.

5.2.2.3 *Climate monitoring*

Rainfall was measured using an Onset HOBO RX3000 remote telemetered monitoring station (Onset HOBO S-RCF-M002 0.2 mm rain gauge measuring every one minute) and installed in an open area away from trees (Onset Computer Corporation, USA). Rainfall interception was not calculated in the kānuka pasture plots. For each surface runoff generating event, the rain amount (mm), rain intensity (mm min^{-1}) and rain duration (hr) was calculated. Rainfall intensity was calculated as the maximum five-minute intensity but converted to mm min^{-1}. An independent rainfall event was defined as being separated by a 6 hour period of no recorded rain (Chen et al., 2018; Renard et al., 1997; Wischmeier, 1959). The independent rainfall event was verified to make sure it aligned with surface runoff recorded by the telemetered tipping bucket sensors.

5.2.2.4 *Soil sampling and analysis*

For soil chemical analysis, 30 soil cores were sampled (0–7.5 cm) in a grid pattern within each plot and bulked to form one sample per plot in May 2021. Samples were analysed for organic matter (Dumas combustion was used to calculate total carbon and organic matter was 1.72 x total carbon) (Nelson and Sommers, 1996), pH (1:2 soil to water) (Blakemore et al., 1987), Olsen-P (30 minute bicarbonate extraction followed by Molybdenum Blue Colorimetry) (Olsen et al., 1954), total-N (Dumas combustion) (Nelson and Sommers, 1996), ammonium-N (0.1 M KCl extraction followed by Berthelot colorimetry) (Keeney and Nelson, 1992), nitrate-N (0.1 M KCl extraction followed by Cd reduction and NED colorimetry) (Keeney and Nelson, 1992), sulphate-S (0.02 M potassium phosphate extraction followed by Ion Chromatography) (Searle, 1988), potassium/calcium/magnesium/sodium (K/Ca/Mg/Na, 1 M neutral ammonium acetate extraction followed by ICP-OES) (Blakemore et al., 1987) and cation exchange capacity (CEC, summation of the extractable cations (K, Ca, Mg, Na) and extractible acidity) (Hesse, 1971).

Bulk density was measured using 6 cm cores taken between 2–8 cm, which were excavated and trimmed. Ten cores were sampled from each plot, with two replicate cores taken from five positions (A, B, C, D and E) within each plot in August 2021. Position A and B were in the top left and top right quarter of the plot, respectively, position C was in the middle of the plot, and plot D and E were in the bottom left and right quarter, respectively. Cores were oven dried at 100 °C and weighed, then bulk density calculated based on the volume of the core (Gradwell and Birrell, 1979). Porosity was calculated by dividing the bulk density by a standard particle density of 2.65 g cm^{-3} (Flint and Flint, 2002). Volumetric soil moisture (VSM) was measured from 0–30 cm after each surface runoff event from September 2020 to May 2021 from each plot using time domain reflectometry (MiniTrase 6050X3K5B, Soilmoisture Equipment Corporation, USA). VSM was measured using five metal probe pairs which were permanently placed in each plot at the positions A, B, C, D and E. VSM was measured ~5 months after the study began to help explain the surface runoff results being measured (this was also the case for the grass height measurements explained in Pasture sampling 5.2.2.5).

5.2.2.5 *Pasture sampling*

Grass height as a proxy for ground cover was measured after every surface runoff event from September 2020 to May 2021. A transect was placed from the top left to the bottom right corner of each plot, and grass height was measured 60 times (measurement accuracy of 0.5 cm) every 10 cm for 6 m using a purpose-built grass height ruler. Measurements began 1.25 m from the start of the transect at the top of the plot and went for 6 m to avoid potential plot edge effects at the top and bottom of the plot. At each measuring point, the grass height ruler had a small platform (0.5 cm x 2 cm) that was lowered down until it touched any undisturbed grass. The ruler recorded the highest point at each of the measurement positions of the undisturbed grass. Bare soil was calculated using (1):

$$\text{Plot bare soil} = \frac{\text{Number of 0 cm measurements}}{\text{60 (the number of measurements per plot)}} \times 100 \tag{1}$$

Pasture standing biomass was measured in each plot position A, B, D and E four times throughout the year (twice in spring, once in summer, once in autumn) to assess the role pasture biomass may have played in buffering surface runoff. Grass was harvested to a height of 1 cm see López et al. (2003b) for more details on the method) with electric clippers from a 0.25 cm x 0.5 cm quadrat. Each sample was dried for 72 hours at 70 °C and weighed. Pasture biomass measurements were performed four times throughout the year to minimise the impact of removing pasture cover on subsequent surface runoff events. A subsample from the autumn biomass measurement was analysed for botanical composition. Individual grass species, dicotyledons and dead matter were separated and dried for 72 hours at 70° C and weighed. In each subsample, grass species and dicotyledon percentage composition were calculated as a percentage of the total weight and the total weight minus dead matter (live matter).

5.2.3 Statistical analysis

Generalised linear models (GLM) were used to compare the means for surface runoff volume and sediment and nutrient loads and concentrations per event because data were highly skewed, and the variances were not homogeneous (Crawley, 2013). Surface runoff volume, nitrate-N concentration, total-N load, nitrate-N load, ammonium-N load, total-P load and DRP load used a Gamma log-link function. Suspended sediment concentration and load, and total-N, ammonium-N, total-P and DRP concentrations used an inverse gaussian link function. A percentile bootstrap method of Kendall's tau was used to test associations between continuous variables (allows for heteroscedasticity) (Wilcox, 2017).

Generalised additive models (GAM) were used to model the relationships between predictor and response variables. GAM and GLM are similar in that non-parametric residuals can be modelled, however, GAM can form non-linear relationships (Wood, 2006). GAMs were used to model the relationships because the Akaike Information Criterion (AIC) showed that the GAMs lost less information than GLMs (Crawley, 2013). Knots (k) were set at 10, although if the models overfit, they were adjusted accordingly (Wood, 2006). Restrictive maximum likelihood estimates (REML) were used to estimate the smoothing parameter (Wood, 2011). All relationships were modelled as univariate GAMs. The effective degrees of freedom (EDF) has been given for each GAM model (Wood, 2006). EDF can be used as proxy for non-linearity; the greater the EDF, the greater the non-linearity (Zuur et al., 2009). If the EDF is close to 1, this indicates the relationship is equivalent to a linear relationship.

Surface runoff was modelled as a function of rainfall amount, rainfall intensity and rainfall duration (all used a Gamma log-link function). Surface runoff and rainfall variables (amount, intensity and duration) were first modelled using a multivariate GAM, however, the concurvity values for each predictor were all close to or greater than 0.5 (Wood, 2006). This indicates that the predictors were all highly related which inflates the probability of type 1 errors (Barton et al., 2020; He, 2004; Ramsay et al., 2003). Therefore, these rainfall variables were modelled as univariate GAMs.

Surface runoff was modelled as a function of grass height and VSM (both used a Gamma log-link function). Bare soil was only modelled in kānuka pasture as there was very little bare soil in open pasture (no link function was used). All loads (suspended sediment, total-N, nitrate-N, ammonium-N, total-P and DRP) were modelled as a function of surface runoff (all used a Gamma log-link function). All predictors and responses were modelled together within the treatment levels except for the loads as the models did not fit well when this was done. Separate models were made for each load within each treatment.

Repeated measurements (measurements taken from the same point at different times) for positions in each plot for grass height, grass biomass, VSM and botanical composition (live and dead proportional weights) were averaged and statistically compared between kānuka and open pasture. Bare soil measurements were not statistically compared between groups as there was one measurement per plot when the repeated measures were averaged (n = 3 per treatment). As samples were bulked for soil fertility cores, there was one soil fertility measurement per plot, so these were also not statistically compared between treatments (n = 3 per treatment). GLMs were used to statistically compare grass height and grass biomass with Gamma log-link functions, and an analysis of variance (ANOVA) test was used to compare bulk density and porosity as the model residuals followed a normal distribution and variances were homogeneous. As the botanical composition had many 0 values the non-parametric/rank-based Cliff's method was used to compare groups (this method allows for heteroscedasticity) (Cliff, 1996; Wilcox, 2017).

The software R (v.4.1.1) (R Core Team, 2021) was used for the statistical analysis. The R package 'mgcv' was used to form the GAMs and GLMs (Wood, 2011) and the robust statistical method functions (percentile bootstrap method of Kendall's tau and Cliff's method) were created by Wilcox (2017).

5.3 Results

5.3.1 Rainfall and surface runoff

There were 23 runoff generating rainfall events during the study period (Table 5.1). The cumulative runoff amounts over the year was 54.0 mm in kānuka pasture (7.0% of annual rainfall) and 7.6 mm in open pasture (1.0% of annual rainfall). There was of 774.6 mm of rain during the study year. 568.8 mm of this rain fell during the 23 runoff generating rainfall events (73.4% of total rain).

Within individual events, surface runoff averaged 8.8% (range: 0.2–24.7%) of rainfall in kānuka pasture, and 1.2% (range: 0.1–7.9%) of rainfall in open pasture. In kānuka pasture, average surface runoff in the three replicated plots was 2.8 mm (plot 1), 1.7 mm (plot 2) and 2.5 mm (plot 3), and in open pasture it was 0.5 mm (plot 4), 0.2 mm (plot 5) and 0.3 mm (plot 6). When split between season, the average surface runoff in spring, summer, winter and autumn per event in kānuka pasture was 2.2 mm, 2.8 mm, 1.8 mm and 2.8 mm, respectively, and in open pasture it was 0.4 mm , 0.7 mm , 0.2 mm and 0.2 mm, respectively.

Table 5.1. Surface runoff generating rainfall event variables and surface runoff.

Date[1]	Rain amount[2] (mm)	Rain duration (hr)	Rain intensity[3] (mm min^{-1})	Surface runoff[4] (mm)	
				Kānuka pasture	Open pasture
26/05/2020	27.0	20.1	0.08	4.3	0.2
04/06/2020	38.2	20.6	0.20	3.2	0.1
18/06/2020	52.2	44.1	0.24	2.8	0.3
29/06/2020	8.8	14.1	0.16	0.1	0.02
01/07/2020	38.8	52.0	0.20	1.9	0.6
08/07/2020	17.0	8.3	0.20	0.1	0.02
06/09/2020	17.4	3.1	0.24	3.7	0.3
10/09/2020	26.6	21.2	0.16	2.5	0.2
18/09/2020	28.2	9.1	0.24	2.6	0.2
28/09/2020	19.0	13.9	0.24	1.2	0.1
27/10/2020	17.2	21.9	0.08	0.8	0.1
10/11/2020	42.4	15.3	0.24	6.4	0.3
18/11/2020	29.8	14.7	0.24	1.1	0.1
25/11/2020	17.6	24.6	0.08	0.03	0.02
26/11/2020	24.2	0.7	0.92	5.8	1.9
30/11/2020	23.4	19.6	0.16	0.1	0.2
08/01/2021	7.4	2.6	0.12	0.8	0.1
16/02/2021	33.0	28.5	0.16	2.9	0.4
11/03/2021	37.4	22.2	0.56	4.7	1.6
31/03/2021	29.2	15.7	0.24	7.2	0.8
17/04/2021	10.8	11.7	0.48	0.2	0.03
12/05/2021	15.6	31.1	0.12	1.2	0.02
17/05/2021	7.6	5.0	0.60	0.4	0.03
Mean	24.7	18.3	0.3	2.3 a***	0.3 b
Range	7.4–52.2	0.07–52.02	0.08–0.9	0.03–7.2	0.02–1.9
Cumulative total	568.8			54.0	7.6

[1] The date when the majority (> 50%) of rainfall fell for this surface runoff generating event.

[2] Independent rainfall events were separated by 6 hour no-rainfall windows.

[3] Intensity was calculated as the amount of rain over a 5 minute period, but shown in mm min^{-1}.

[4] If the letters differ, this indicates that treatment values are significantly different.

*** = Significant to the p < 0.001 level.

There was a slightly significant positive association between rain amount and rain duration ($n = 23$, $R = 0.36$, $p < 0.05$) and no significant association between rain amount and intensity ($n = 23$, $R = 0.14$, $p > 0.05$), and between rain intensity and rain duration ($n = 23$, $R = -0.30$, $p > 0.05$).

5.3.2 Surface runoff predictor variables

There was a significant positive association between surface runoff amount and rain amount in kānuka pasture (n = 23, R = 0.45, p < 0.001) and open pasture (n = 23, R = 0.45, p < 0.01). There was not a significant association between surface runoff amount and rain intensity or rain duration in both kānuka pasture (rain intensity: n = 23, R = 0.25, p > 0.05; rain duration: n = 23, R = 0.028, p > 0.05) or open pasture (rain intensity: n = 23, R = 0.26, p > 0.05; rain duration: n = 23, R = 0.071, p > 0.05). When modelled as smoothed functions, there was a significant relationship between s(surface runoff amount) and rain amount in kānuka pasture and rain amount and rain intensity in open pasture (Figure 5.3).

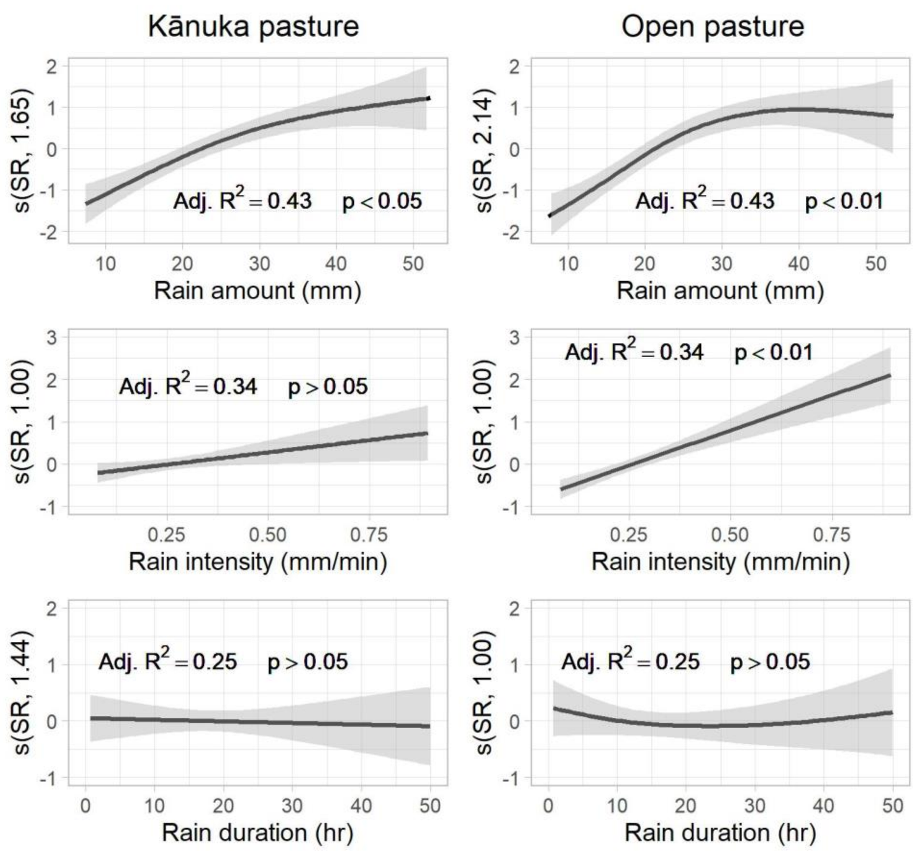

Figure 5.3. Univariate GAMs between rain amount, rain intensity and rain duration and surface runoff amount in kānuka pasture and open pasture. For each model, the bracket in the y-axis description contains the response variable (SR = surface runoff amount) and the effective degrees of freedom (EDF). The 's' indicates the response term is smoothed. The shaded areas are the 95% confidence intervals.

There was not a significant association in kānuka pasture between surface runoff amount and grass height (n = 16, R = -0.083, p > 0.71), VSM (n = 13, R = 0, p > 0.05) or bare soil (n = 16, R = -0.033, p > 0.05). There was not a significant association in open pasture between surface runoff amount and grass height (n = 16, R = 0.083, p > 0.05) or VSM (n = 13, R = 0.23, p > 0.05). When modelled as smoothed functions, no significant relationships were found between surface runoff and grass height, VSM and bare soil (Table 5.2).

Table 5.2. Univariate GAMs for surface runoff amount as a function of grass height, VSM and bare soil.

Variable	Treatment	n	EDF	*F*-value	*P*-value	Deviance explained (%)	Adj.R^2
Grass height	Kānuka pasture	16	0.000015	0.00	0.91	39.00	0.25
	Open pasture		1.033	1.73	0.051		
VSM	Kānuka pasture	13	0.000013	0.00	0.94	26.30	0.20
	Open pasture		1.22	0.077	0.27		
Bare soil	Kānuka pasture	16	0.000027	0.00	0.99	0.0000018	0.0000028

EDF = effective degrees of freedom. VSM = volumetric soil moisture.

5.3.3 Sediment and nutrient loads and concentrations

Nutrient concentrations were in general greater in kānuka pasture, except for the mean and median of suspended sediment and ammonium-N (Table 5.3; Table 5.4). The mean concentrations of ammonium-N and total-N were disproportionally impacted by extreme values and so the median gives a better representation of a central value. Median concentrations of total-N, nitrate-N, total-P and DRP were 74.2%, 660.0%, 116.6% and 120.0% greater in kānuka pasture compared to open pasture, respectively. All nutrient loads were significantly greater in kānuka pasture. Annual cumulative load was also greater in kānuka pasture for all sediment and nutrient loads.

In kānuka pasture, the cumulative suspended sediment annual load in plot 1, plot 2 and plot 3 was 31.0 kg ha^{-1} yr^{-1}, 12.2 kg ha^{-1} yr^{-1} and 13.5 kg ha^{-1} yr^{-1}, respectively. In open pasture it was 6.6 kg ha^{-1} yr^{-1}, 1.7 kg ha^{-1} yr^{-1} and 2.9 kg ha^{-1} yr^{-1} in plot 4, plot 5 and plot 6, respectively. The cumulative total-N annual load in kānuka pasture in plot 1, plot 2 and plot 3 was 6.2 kg ha^{-1} yr^{-1}, 3.1 kg ha^{-1} yr^{-1} and 7.5 kg ha^{-1} yr^{-1}, respectively, and in open pasture it was 0.3 kg ha^{-1} yr^{-1}, 0.2 kg ha^{-1} yr^{-1}, 0.3 kg ha^{-1} yr^{-1} in plot 4, plot 5 and plot 6, respectively. The cumulative total-P annual load in kānuka pasture in plot 1, plot 2 and plot 3 was 2.6 kg ha^{-1} yr^{-1}, 1.1 kg ha^{-1} yr^{-1} and 2.7 kg ha^{-1} yr^{-1}, respectively, and in open pasture it was 0.2 kg ha^{-1} yr^{-1}, 0.1 kg ha^{-1} yr^{-1}, 0.1 kg ha^{-1} yr^{-1} in plot 4, plot 5 and plot 6, respectively.

Table 5.3. Sediment and phosphorus concentration, loads and cumulative loads.

Treatment		SS[a]	Total-P[b]	DRP[b]
		Concentration (g m^{-3})		
Kānuka pasture	Mean	39.3 a	4.4 a	3.8 a
	Median	27.0	3.9	3.3
	Range	9.1–177.7	2.2–8.9	1.4–8.0
Open pasture	Mean	55.5 a	3.4 a	2.9 a
	Median	42.9	1.8	1.5
	Range	11.1–153.0	0.9–14.0	0.6–12.6
		Load (kg ha^{-1})		
Kānuka pasture	Mean	1.2 a	0.1 a***	0.09 a***
	Median	0.7	0.1	0.08
	Range	0.02–9.9	0.002–0.3	0.002–0.2
Open pasture	Mean	0.3 a	0.009 b	0.007 b
	Median	0.06	0.003	0.002
	Range	0.01–2.4	0.0005–0.06	0.0004–0.05
		Cumulative mean annual load (kg ha^{-1} yr^{-1})		
Kānuka pasture		18.9	2.1	1.8
Open pasture		3.7	0.1	0.1

[a] SS = suspended sediment; n = 18.
[b] n = 19.
If the letters differ, this indicates that treatment values are significantly different. ***= Significant to the $p < 0.001$ level. P = Phosphorus.

Table 5.4. Nitrogen concentration, loads and cumulative loads.

Treatment		Total-N[a]	Nitrate-N[a]	Ammonium-N[a]
		Concentration (g m^{-3})		
Kānuka pasture	Mean	13.4 a	4.9 a**	2.0 a
	Median	11.5	3.8	1.1
	Range	5.6 – 42.2	0.7 – 11.0	0.3 – 9.5
Open pasture	Mean	12.8 a	1.3 b	4.6 a
	Median	6.6	0.5	1.8
	Range	1.8 – 76.0	0.2 – 9.5	0.2 – 33.3
		Load (kg ha^{-1})		
Kānuka pasture	Mean	0.3 a***	0.1 a***	0.03 a***
	Median	0.2	0.09	0.02
	Range	0.007 – 0.9	0.003 – 0.5	0.002 – 0.1
Open pasture	Mean	0.02 b	0.001 b	0.004 b
	Median	0.01	0.0009	0.003
	Range	0.003 – 0.06	0.00007 – 0.003	0.0009 – 0.01
		Cumulative mean annual load (kg ha^{-1} yr^{-1})		
Kānuka pasture		5.6	2.2	0.6
Open pasture		0.3	0.02	0.07

[a] n = 19.

If the letters differ, this indicates that treatment values are significantly different. **= Significant to the p < 0.01 level; ***= Significant to the p < 0.001 level. N = Nitrogen.

5.3.4 Surface runoff and sediment and nutrient load and concentration relationships

There was a significant negative association between concentration and surface runoff in both treatments for total-N (n = 19, kānuka pasture: R = -0.37, $p < 0.05$; open pasture: R = -0.45, $p < 0.05$) and ammonium-N (n = 19, kānuka pasture: R = -0.42, $p < 0.05$; open pasture: R = -0.46, $p < 0.05$). There was a significant negative association for nitrate-N in open pasture (n = 19, R = -0.46, $p < 0.05$), but not for kānuka pasture (n = 19, R = -0.33, $p > 0.05$). There was not a significant association between concentration and surface runoff in either treatment for suspended sediment (n = 18, kānuka pasture: R = -0.098, $p > 0.05$; open pasture: R = -0.19, $p > 0.05$), total-P (n = 19, kānuka pasture: R = -0.23, $p > 0.05$; open pasture: R = -0.26, $p > 0.05$) and DRP (n = 19, kānuka pasture: R = -0.27, $p > 0.05$; open pasture: R = -0.31, $p > 0.05$).

There were significant positive associations between loads and surface runoff amounts in both treatments for suspended sediment (n = 18, kānuka pasture: R = 0.54, $p < 0.001$; open pasture: R

= 0.70, $p < 0.001$), total-N ($n = 19$, kānuka pasture: $R = 0.77$, $p < 0.001$; open pasture: $R = 0.64$, $p < 0.001$), nitrate-N ($n = 19$, kānuka pasture: $R = 0.63$, $p < 0.001$; open pasture: $R = 0.50$, $p < 0.01$), total-P ($n = 19$, kānuka pasture: $R = 0.77$, $p < 0.001$; open pasture: $R = 0.73$, $p < 0.001$) and DRP ($n = 19$, kānuka pasture: $R = 0.72$, $p < 0.001$; open pasture: $R = 0.72$, $p < 0.001$), and only in kānuka pasture for ammonium-N ($n = 19$, $R = 0.44$, $p < 0.05$). There was not a significant association between ammonium-N load and surface runoff in open pasture ($n = 19$, $R = 0.30$, $p > 0.05$).

Figure 5.4 shows the univariate GAM model effects, with all but ammonium-N nutrient loads and nitrate-N in open pasture showing a positive trend with increasing surface runoff in both treatments. Suspended sediment also showed a positive trend with surface runoff in kānuka pasture and open pasture, although the models did not fit well for suspended sediment because of high variability.

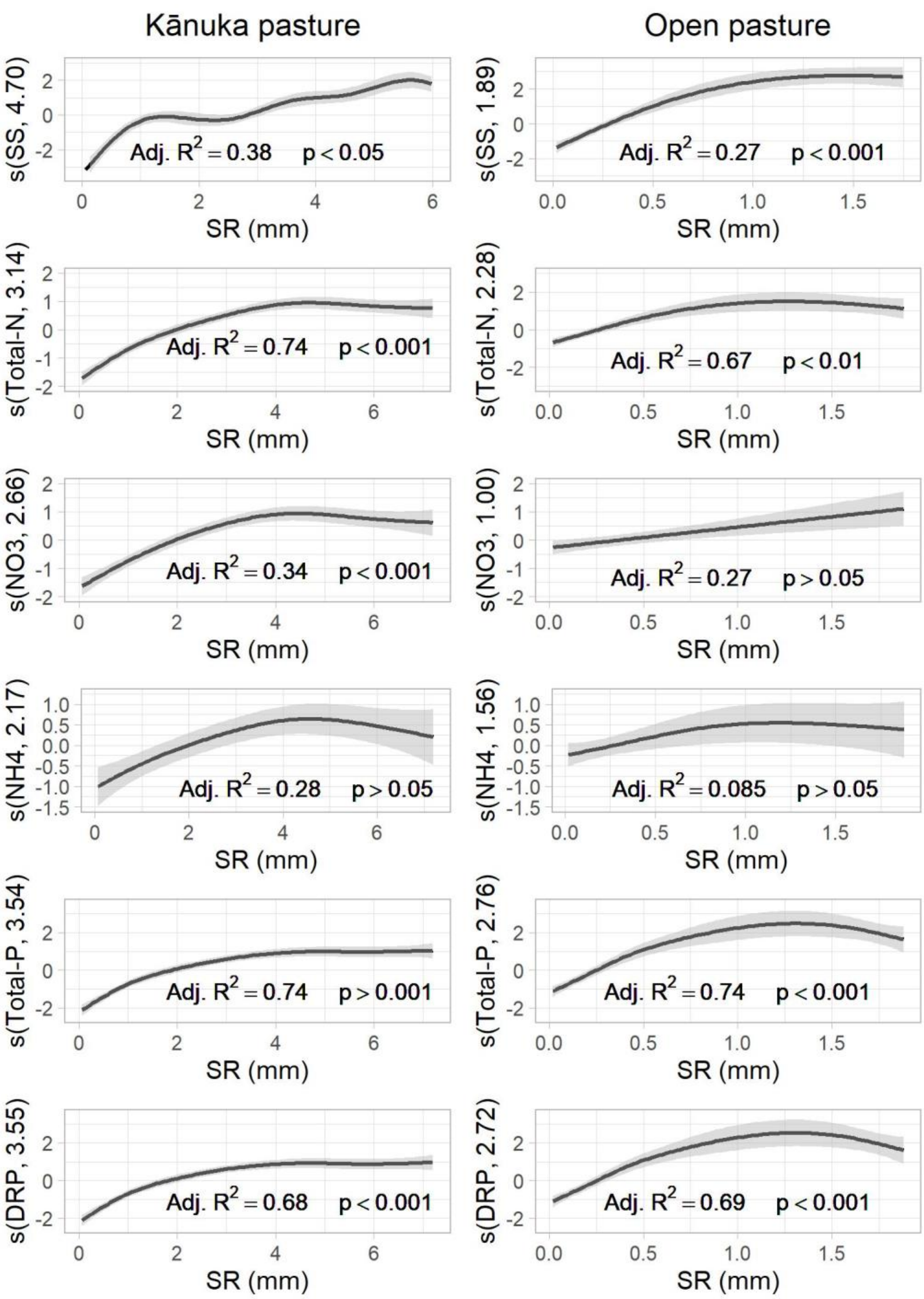

Figure 5.4. Univariate GAMs between sediment and nutrient loads as a function of surface runoff (SR) in kānuka and open pasture. For each model, the bracket in the y-axis description contains the response variable (SS = suspended sediment, NO3 = nitrate-N, NH4 = ammonium-N), and the effective degrees of freedom (EDF). The 's' indicates the response term is smoothed. The shaded areas are the 95% confidence intervals. P = Phosphorus. N = Nitrogen.

5.3.5 Vegetation and soil variables

Kānuka pasture had significantly less standing grass biomass ($p < 0.001$) and grass height ($p < 0.001$) than open pasture (Table 5.5). Bare soil was greater in kānuka pasture. Despite bare soil being on average 5.6% in kānuka pasture, it was concentrated in plot 3, which had 14.2% of bare soil. Plot 1 and plot 2 had an average of 1.9% and 0.7%, respectively. Bare soil in plot 4, plot 5 and plot 6 was 0.1%, 0.3% and 0.1% respectively. Olsen-P, nitrate-N, total-N, sulphate-S, organic matter and CEC were 89.0%, 505.9%, 66.6%, 28.9%, 111.6% and 53.9% higher in kānuka pasture. Ammonium-N was 107.7% greater in open pasture, and pH was also greater in open pasture. VSM was significantly greater in open pasture ($p < 0.001$) and porosity was significantly greater in kānuka pasture ($p < 0.001$). As the highest value recorded for VSM was below the porosity, at no measurement time was the soil at the sites saturated.

There was significantly more perennial ryegrass ($p < 0.001$) and cocksfoot ($p < 0.001$) (both live weight and total weight) in kānuka pasture, and significantly more danthonia spp. in open pasture ($p < 0.001$) (Table 5.6). Live matter was greater in kānuka pasture and less in open pasture, although these differences were not significant.

Table 5.5. Vegetation and soil measurements for each treatment. Ranges are given in brackets.

Variable	Kānuka pasture	Open pasture
Grass height[a] (cm)	9.6 b (0.0–55.0)	18.2 a*** (0–51.0)
Standing grass biomass[b] (kg ha^{-1})	815.9 b (124.4–1833.4)	2527.0 a*** (700.7–5606.5)
Bare soil[c] (%)	5.6 (0.7–14.1)	0.2 (0.1–0.3)
pH[c]	5.6 (5.9–6.1)	6.0 (5.9–6.1)
Olsen P[c] (mg L^{-1})	63.7 (60.0–67.0)	33.7 (30.0–37.0)
Nitrate-N[c] (mg kg^{-1})	10.3 (6.0–17.0)	1.7 (1.0–2.0)
Ammonium-N[c] (mg kg^{-1})	1.3 (1.0–2.0)	2.7 (2.0–3.0)
Total – N[c] (%)	0.5 (0.4–0.6)	0.3 (0.3–0.3)
Sulphate-S[c] (mg kg^{-1})	10.7 (9.0–13.0)	8.3 (8.0–9.0)
Organic matter[c] (%)	12.7 (10.8–15.5)	6.0 (5.7–6.5)
CEC[c] (me $100g^{-1}$)	25.7 (24.0–27.0)	16.7 (16.0–17.0)
K[c] (me $100g^{-1}$)	0.9 (0.8–1.1)	0.7 (0.5–0.89)
Ca[c] (me $100g^{-1}$)	10.7 (9.8–11.7)	8.5 (7.8–9.0)
Mg[c] (me $100g^{-1}$)	3.0 (2.7–3.4)	2.7 (2.6–2.9)
N[c] (me $100g^{-1}$)	0.4 (0.3–0.5)	0.2 (0.2–0.2)
VSM[d] (%)	21.4 b (11.9–37.8)	27.3 a*** (14.2–38.0)
Bulk density[e] (g cm^{-3})	1.0 b (0.9–1.3)	1.2 a*** (1.0–1.5)
Porosity[e] (%)	61.1 a*** (50.5–66.8)	53.5 b (44.7–60.8)

[a] If the letters differ, this indicates that treatment values are significantly different.

[a] n = 60

[b] Standing grass biomass is spot measurements of the amount of grass in each treatment and not annual pasture production; n = 15.

[c] n = 3; sample size too small for statistical testing.

[d] n = 10.

[e] n = 30.

If the letters differ, this indicates that treatment values are significantly different. *** Significant to $p < 0.001$. P = Phosphorus. N = Nitrogen. S = Sulphur. CEC = cation exchange capacity. K = potassium. Ca = Calcium. Mg = Magnesium. Na = Sodium. VSM = volumetric soil moisture.

Table 5.6. Live and dead weight botanical composition measurements for each treatment.

Common name	Latin name	Botanical composition as a proportion of live weight (%)		Botanical composition as a proportion of total weight (%)	
		Kānuka pasture[a]	**Open pasture[a]**	**Kānuka pasture[a]**	**Open pasture[a]**
Perennial ryegrass	*Lolium perenne* L.	42.6 a***	9.7 b	16.2 a***	1.9 b
Cocksfoot	*Dactylis glomerata* L.	14.6 a***	0.0 b	6.5 a***	0.0 b
Browntop	*Agrostis capillaris* L.	32.0 a	15.6 a	11.7 a	4.9 a
Sweet vernal	*Anthoxanthum odoratum* L.	6.5 a	18.3 a	2.1 a	3.2 a
Danthonia spp.	*Rytidosperma spp.*	0.0 b	36.5 a***	0.0 b	11.3 a***
Dicotyledon	n/a	4.3 a	20.0 a	1.8 a	5.7 a
Live matter		n/a	n/a	38.2 a	27.0 a
Dead matter		n/a	n/a	73.1 a	61.9 a

[a] n = 15

If the letters differ, this indicates that treatment values are significantly different. *** Significant to $p < 0.001$.

5.4 Discussion

5.4.1 Surface runoff

This study shows that the presence of trees can lead to more surface runoff when compared to paired pasture areas without trees. This is contrary to the review by Zhu et al. (2020), that found a 58% average reduction of surface runoff under agroforestry systems and reported no examples of agroforestry systems increasing surface runoff when compared to equivalent non-agroforestry agricultural or forest areas. Two of these studies were silvopastoral systems and reported reductions of surface runoff between 45% and 88% compared to other land-uses. In a New Zealand study not reviewed by Zhu et al. (2020), Hussain (2009) compared surface runoff in a high density (1.2 m spacing) poplar (*populus* spp.) silvopastoral system and open pasture and found 47% less surface runoff in the silvopastoral system.

The current study results were measured despite kānuka pasture having improved soil conditions; kānuka pasture had greater porosity, Olsen-P, nitrate-N, total-N, sulphate-S, organic matter and

CEC (Table 5.5). Pasture species can also be an indicator of the condition of the pasture, with condition being the overall state of the ecosystem relative to a pasture production benchmark determined under a normal climate and best management practices (Gastó et al., 1993; Humphrey, 1949; Smith, 1973). The significantly greater percentage composition of perennial ryegrass (*Lolium perenne* L.) and cocksfoot (*Dactylis glomerata* L.) are indicative of good pasture condition, whereas the danthonia spp. (*Rytidosperma spp.*) and sweet vernal (*Anthoxanthum odoratum* L.) in open pasture are indicative of poor pasture condition (Gastó et al., 1993; López et al., 2006). The high dead matter proportions in both treatments are typical in hill country in early autumn due to moisture deficits (Figure 5.2B).

The increased surface runoff amount measured in the improved pasture conditions of kānuka pasture is contrary to Lambert et al. (1985), who measured surface runoff in two fertility levels (high and low fertility) in New Zealand hill country and found 33.6% more surface runoff in their low fertility treatment. This is consistent with surface runoff literature in which improved soil condition is associated with less surface runoff due to improvements in soil structure and infiltration (Young, 1989; Zhu et al., 2020). The increased surface runoff measured in the improved soil conditions of kānuka pasture suggests that there are other factors influencing surface runoff processes in these plots.

There was significantly less VSM in kānuka pasture (Table 5.5), despite there being improved pasture conditions (López et al., 2006). This suggests that soil moisture is not driving the pasture condition improvements beneath the trees, and the lower soil moisture in kānuka pasture is most likely a result of the trees' water use and their relatively high density within the plots (~750 tree ha^{-1}), or that there was a low amount of surface runoff in the open pasture plots increasing infiltration into the soil. A reduction in soil moisture may suggest that there would be less surface runoff in kānuka pasture as there would be less chance of the soil becoming saturated as more pore space is available to accommodate rainfall before it becomes saturated. Nevertheless, soil was not saturated during any of the soil moisture measurements in either of the two treatments. Moreover, no trend was found in either of the two treatments between surface runoff and soil moisture.

There was limited evidence of soil repellency in summer or early spring, with soil repellency (hydrophobicity) being when water is repelled by the soil surface in dry conditions because of organic matter (Bretherton et al., 2018). There was slightly more surface runoff in summer compared to all other seasons in open pasture, however, this trend was not found in kānuka pasture which had much more organic matter and became drier in summer.

Bare soil was significantly greater in kānuka pasture, but it was still relatively low (5.6% on average) and concentrated in plot 3 (14.2% compared to 1.9% and 0.7% in plot 1 and plot 2, respectively), despite plot 3 not having the greatest average surface runoff per event in the kānuka pasture treatment (plot 1: 2.8 mm; plot 2: 1.7 mm; plot 3: 2.5 mm). Therefore, bare soil was most likely not the reason for the increase in surface runoff in kānuka pasture.

Vegetation cover has been shown to be a key factor for reducing surface runoff on hill slopes (Chen et al., 2018; El Kateb et al., 2013; Mohammad and Adam, 2010; Zhou et al., 2016; Zhu et al., 2020). In terms of the amount and height of the grass, kānuka pasture had a significantly lower grass height and grass biomass[1]. This grass biomass difference was visible to the eye, with a thick grass cover in open pasture observed throughout the study period that was not often observed in kānuka pasture. No trend existed between grass height and surface runoff in neither treatment. It would be expected that grass biomass would influence surface runoff processes more than grass height as it is the density of grass and roots that would impact the attenuation of surface runoff

[1] It must be stressed that the grass biomass measurement is not the annual dry matter production, but a standing biomass measurement of how much grass was present in the quadrat at the time of measurement.

more than the height of the grass. Therefore, the 209.7% increase in grass biomass in the open pasture treatment is the most likely reason for the very low surface runoff in open pasture, and the increase in surface runoff in kānuka pasture.

A similar result was found by de Aguiar et al. (2010) when comparing surface runoff in a 260 tree ha^{-1} Brazilian silvopastoral system (mainly trees in the families Borragonaceae and Mimosoidea) and native forest, with the authors concluding that the reduction in surface runoff in the silvopastoral system was because of a greater herbaceous cover when compared to native forest. This was also found by Grewal et al. (1994), with reduced surface runoff being recorded in a treatment with 2 m x 2 m *Leucaena leucocephala* (Lam.) de Wit var K-8 growing over napier grass (*Pennisetum purpureum* Schumach.) when compared to a traditional rainfed crop sequence (sesame then rapeseed) and cultivated fallow.

The reduced grass biomass in kānuka pasture was likely the result of livestock preferentially grazing the grass under the kānuka trees when compared to open pasture due to the sheltered conditions or the presence of more favourable grass species (López et al., 2003a). Summers can be very dry in the study location (Bretherton et al., 2018), and many areas of the paddock did not have trees (Figure 5.1C). The results could be the product of an extreme choice for livestock between areas in the paddock with and without tree shelter. Removing this choice for livestock, or dispersing livestock around the paddock by planting more trees, may help mitigate the extreme differences in vegetation cover under and away from the trees.

Only two past silvopastoral studies have compared surface runoff in open pasture and under fully-grown trees in a silvopastoral system, and both of these studies compared surface runoff between silvopastures and arable land (de Aguiar et al., 2010; Grewal et al., 1994). These studies did not measure the difference in vegetation or surface runoff processes when livestock were given a choice between tree and treeless pasture, as in this study. The results of this present study may be different if livestock were grazed in paddocks with just silvopastoral trees and little open pasture, as the grass biomass could be more easily controlled with grazing management.

Moreover, the stocking rate in this study was very high compared to the silvopasture studied by de Aguiar et al. (2010). The high stocking rate over only two to three days grazing will have contributed to animals intensively grazing the pasture under the trees and reduced open pasture grazing. However, even if the stocking rate was reduced, it is likely that the pasture in kānuka pasture would be grazed first, still resulting in reduced grass biomass under the trees.

It is possible that the kānuka trees induced stemflow, which is the flow of intercepted water by the tree down its stem. Nevertheless, stemflow has generally been found to be low in New Zealand native trees. It was on average 1% of rainfall in a high density (3900 stems ha^{-1}) stand of *Kunzea ericoides* var. *ericoides* (A. Rich.) (kānuka) (Rowe et al., 1999), 1.3% of rainfall in *Nothofagus cliffortioides* (Hook.f.) Oerst. (Rowe, 1974), 1.5% of rainfall in a beech-podocarp-hardwood forest (Rowe, 1979) and 2% of rainfall in a *Nothofagus* spp. forest (Rowe, 1983). Even if stemflow was 1% of rainfall in this study (following the stemflow recorded by Rowe et al. (1999) in the kānuka stand), and assuming all this stemflow became measured surface runoff, this would have represented 14.4% of the total surface runoff measured in kānuka pasture. This highlights that stemflow may not have been marginal in the study and further research is required to understand the amount of stemflow in a kānuka silvopastoral system.

Past studies have shown that canopies can increase rainfall drop diameter (Levia et al., 2017; Li et al., 2019; Nanko et al., 2006), and under specific rainfall conditions, increase raindrop kinetic energy (Brandt, 1988; Li et al., 2019). However, the relationship between surface runoff and rain amount in kānuka pasture, and not rain intensity, suggests that the tree canopy is not intensifying surface runoff by increasing the kinetic energy of rainfall.

In terms of relative amounts, the 54.0 mm of surface runoff in kānuka pasture was a lower proportion of total rainfall (7.0%) than past studies that have reported surface runoff in hill country catchments without trees. For example, Gillingham and Gray (2006) found surface runoff to be 18% to 26% of total rainfall in two New Zealand hill country catchments (12.6 ha and 12.8 ha in area). Lambert et al. (1985) found surface runoff in their high and low fertility treatments to be 399 mm (32.0% of total rainfall) and 533 mm (42.7% of total rainfall), respectively, in catchments that varied in size between 0.13 ha and 1.53 ha. These past hill country studies measured surface runoff over a larger area than this study (plots in this study ranged in size between 0.032–0.039 ha). A larger catchment increases the chance that surface runoff is slowed by grass and infiltrated, so because there was much less surface runoff in this study, there is a chance that the surface runoff in Gillingham and Gray (2006) and Lambert et al. (1985) was the result of either channelised flow down their catchments, or the result of less grass biomass on the hill slopes (this was not reported in either study).

Bretherton et al. (2018) also measured specifically 'repellency-induced' surface runoff in 1 m by 2 m plots (smaller than the plots in this study) on 20–30° slopes in hill country and found it to range from 1% to 59% of total rain during nine rainfall events. This shows that surface runoff can be high in small plots as well as larger catchments. The lower surface runoff in this study is encouraging as it shows that in certain conditions surface runoff can be low in New Zealand hill county, even without the presence of trees. It also provides evidence that even in poor soil conditions, surface runoff can be managed by on-farm grazing management, specifically by maintaining grass biomass on pastoral hill slopes. Finally, the relative contribution of the surface runoff in the kānuka pasture environment will vary greatly between paddocks because the number of kānuka growing in different paddocks is highly variable.

A limitation of this study was that it was only done for one year and the annual rainfall at the site (774.6 mm) was below the 30-year average at a weather station 6.7 km from the site (average: 903 mm; min: 545 mm; max: 1297 mm). Therefore, in a wetter year, surface runoff under the trees would have most likely been more. Moreover, if rainfall events increase in intensity or amounts due to changing climates (Caloiero, 2015), this will impact surface runoff in the future. Nevertheless, as surface runoff was very low in open pasture, which was most likely due to the grass biomass, livestock effects should have more influence on surface runoff processes at this site compared to rainfall variability.

5.4.2 Sediment

In both kānuka and open pasture, sediment loads were a function of surface runoff, with increased surface runoff resulting in increased sediment loads. This was also found by Chen et al. (2018) and Zhou et al. (2016) in hill slopes of the Loess Plateau in China, and provides evidence that sediment loads can be reduced by mitigating surface runoff, and sediment losses via sheet erosion can be managed by on-farm practices that maintain vegetation cover.

Sediment loads were substantially greater in kānuka pasture (18.9 kg ha^{-1} yr^{-1}) compared to open pasture (3.7 kg ha^{-1} yr^{-1}) (Table 5.3). However, this was a function of the greater surface runoff in kānuka pasture, rather than an increase in the amount of sediment lost per unit of water as the suspended sediment concentration in the surface runoff in kānuka and open pasture were statistically similar. This result is surprising as organic matter was 52.8% less in open pasture, and it would be expected that there would be an increase in suspended sediment concentration in surface runoff from soil with poorer organic matter as soil stability is positively related to an increase in organic matter (Ekwue, 1990; Morgan, 2005). Raindrop soil detachment has been shown to decrease exponentially from 0% organic matter soil proportions to 12% (Ekwue, 1990). Organic matter was 6.0% and 12.7% in open and kānuka pasture, respectively, so it is surprising that suspended sediment had similar concentrations in surface runoff between treatments. Like for surface runoff, this suggests that there were other processes than soil conditions driving sediment loss.

Due to the impact of trees on raindrop size and velocity, Wiersum (1985) found trees increased the erosive power of rainfall by 24% under a 5-year old plantation of *Acacia auriculiformis* A.Cunn.

at 650 trees ha^{-1} in Indonesia. Nevertheless, in their study, 11.8% less rainfall reached the ground, which is the most likely reason why their treatment 'no soil cover, no tree canopy' had slightly more sediment loss than 'no soil cover, with a tree canopy' (Wiersum, 1985). Wiersum (1985) found direct soil cover to be the most important factor determining sediment loss, more important than the influence of a tree canopy. Tree canopies had minimal influence on sediment loss as two treatments with and without a tree canopy but both with a litter layer had similar levels of sediment loss, and the presence of a vegetative undergrowth in two other treatments with and without a tree canopy further reduced sediment loss by similar amounts (Wiersum, 1985). De Aguiar et al. (2010) came to a similar conclusion when comparing their silvopastoral system in Brazil with a native forest treatment, with the silvopastoral system losing less sediment because of a greater herbaceous cover. These findings are consistent with the conclusion in the previous section that despite soil condition improvements beneath the trees (in terms of porosity and organic matter) (Table 5.5), increased grass biomass was the most likely reason for the reduced annual loads of sediment loss in open pasture because of its influences on surface runoff. Moreover, if the grass biomass was lower in open pasture, because of the reduced organic matter in this treatment, the sediment concentration in surface runoff would most likely have been greater in open pasture compared to what was recorded in this study.

Like surface runoff, sediment losses were also small compared to past studies in hill country. In their review of nine mixed sheep and beef catchments, McDowell and Wilcock (2008) found an average sediment loss of 1156 kg ha^{-1} yr^{-1}, compared to 18.9 kg ha^{-1} yr^{-1} in kānuka pasture and 3.7 kg ha^{-1} yr^{-1} in open pasture. There are two likely reasons for these differences. The first is the grass biomass found on the hill slopes in this present study, although standing grass biomass was not measured in these past studies. Moreover, the catchments reviewed by McDowell and Wilcock (2008) were larger in size than the plots in this study. Despite water movement length being shown to be negatively associated with sediment loss (Lei et al., 2002), these large catchments contain more highly erosive features which may enhance soil and water movement, such as extensive bare soil patches, tracks, channelised flow areas, stream banks, areas of cropland or gullies. The results of this study are therefore evidence that sediment loss can be low in plot scale studies on hill country slopes, with or without trees, especially in areas that maintain a high density of grass on slopes, and suggests that sediment loss research should focus on highly erosive sediment sources.

5.4.3 Nutrients

As nutrient loads were almost all significantly positively related to surface runoff, mitigation methods for reducing nutrient loads should focus on mitigating surface runoff. The nutrient load differences between kānuka and open pasture were very large, with the annual cumulative loads between 10 times to 100 times greater in kānuka pasture. The greater nutrient loads beneath the trees is contrary to the 47% average nutrient loss reduction found in silvopastoral systems by Zhu et al. (2020). The main reasons for this nutrient loss reduction in silvopastoral systems are trees reducing surface runoff and sediment loss and thus associated nutrient loss (de Aguiar et al., 2010), or nutrient uptake by the trees (Michel et al., 2007; Nair et al., 2007; Zhu et al., 2020).

In the USA, Nair et al. (2007) measured soil nitrate-N, ammonium-N and water-soluble P under slash pine (*Pinus elliotti* Engelm.) silvopastoral systems of 494 trees ha^{-1} and 309 trees ha^{-1}, native silvopastoral systems (no density was given) and treeless pasture. The authors found nutrient loss reductions ranged from 30% to 83% in the silvopastoral systems when compared to open pasture. The authors concluded these reductions were because of nutrient uptake by the trees. A similar conclusion was found by Michel et al. (2007) when measuring soil water-soluble P under slash pine systems compared to treeless pasture at four sites in the USA, Bambo et al. (2009) when measuring nitrate-N leaching under loblolly pine (*Pinus taeda* L.) silvopastures compared to treeless pastures in the USA, and in a greenhouse experiment comparing nitrate-N leaching under cherry (*Prunus avium* (L.) L.) and pasture compared to just pasture (López-Díaz et al., 2011).

Contrary to these past studies, the elevated nutrient concentrations in kānuka pasture surface runoff corresponds to greater nutrient concentrations within the soil of this treatment. This is especially so for nitrate-N, as there was 10.3 mg kg^{-1} of nitrate-N recorded in kānuka pasture soil but only 1.7 mg kg^{-1} recorded in open pasture soil, and there was a 660.0% greater nitrate-N concentration recorded in surface runoff in kānuka pasture when comparing the medians. This was also the case for P, with Olsen-P in kānuka pasture being 89.0% greater than in open pasture, and the medians of total-P and DRP concentrations in surface runoff being 116.6% and 120.0% greater in kānuka pasture, respectively.

The only inconsistency in the nutrient loss results was the 65.5% greater ammonium-N concentration in open pasture surface runoff. This increased ammonium-N concentration is consistent with the 107.7% increase of ammonium-N in open pasture soil, although the ammonium-N soil results were low in both treatments (1.3 mg kg^{-1} in kānuka pasture, 2.7 mg kg^{-1} in open pasture). One possible reason for this difference was a higher deposition of N in animal dung and urine under the trees that will support a higher population of nitrifying bacteria (McLaren and Cameron, 1996). This could increase the conversion of ammonium-N to nitrate-N, lowering the ammonium-N in soil and surface runoff in kānuka pasture. Further evidence for this is the more acidic soil in kānuka pasture, as the conversion of ammonium-N to nitrate-N releases H^+ ions (Gundersen and Rasmussen, 1990). Nevertheless, a nutrient balance was not undertaken in this study so further work is required to confirm this.

Along with pasture cover variation between treatments, these nutrient concentration treatment differences are further evidence that livestock intensively use the kānuka pasture environment, depositing nutrient rich dung and effluent in the kānuka pasture treatment. This would explain the substantially greater P concentrations in the soil and surface runoff of kānuka pasture, and the more mobile N environment. The results are evidence that nutrients are deposited and lost in kānuka pasture at a much greater rate than the nutrient uptake by the trees. Nutrient transfer normally happens from high to low sloped areas in hill country (López et al., 2003b; Saggar et al., 1990). Nevertheless, this study provides evidence that nutrient transfer can happen from open areas to under trees.

Although the field studies that found evidence for reduced soil nutrients because of tree uptake did not specifically say (Bambo et al., 2009; Michel et al., 2007; Nair et al., 2007), these studies most likely grazed each land-use separately, because they were referred to as separate systems in the study descriptions (silvopastoral systems and treeless pasture system), and Bambo et al. (2009) mentioned each treatment was replicated as 0.54 ha areas. This contrasts with this study as livestock were in the same paddock as the treatments. Like for surface runoff and the reduced grass biomass under the kānuka trees, the build-up of nutrients in this study could therefore be an important consideration in silvopastoral system designs where there are many open areas in the paddock, and livestock have a choice between open and tree pasture areas.

The other three mechanisms that may have created these nutrient environment differences are tree litterfall, tree root decomposition and bird excretion. Although litterfall or root distribution was not tested, there was little litterfall observed during pasture measurements and relatively few roots were seen in the topsoil in kānuka pasture. Moreover, if leaf or root composition by kānuka pasture was the driver of pasture condition improvements, we would not expect such large treatment differences between nitrate-N and DRP concentrations in surface runoff, as these are very mobile nutrient forms normally resulting from animal excreta. Finally, although bird use of the trees was also not tested, roosting birds were not seen to use the trees in excessively high numbers (day or night).

In terms of relative amounts, although surface runoff volume and sediment loads were low compared to past hill country literature, nutrient loads were not. In the review by McDowell and Wilcock (2008), average total-N and total-P losses were 11 kg ha^{-1} yr^{-1} (range: 5–22 kg ha^{-1} yr^{-1})

and 1.3 kg ha^{-1} yr^{-1} (range: 0.3–2.1 kg ha^{-1} yr^{-1}), respectively, for mixed sheep and cattle catchments, compared to average total-N losses of 5.6 kg ha^{-1} yr^{-1} and total-P losses of 2.1 kg ha^{-1} yr^{-1} in the kānuka pasture in this study. The acute P losses in this study suggests a particular build-up of livestock excretion beneath the trees, and gives evidence that the trees were acting as a livestock camping spot. These results are a concern for hill country pastoral management, especially as surface runoff in this study was low compared to past studies (Bretherton et al., 2018; Gillingham and Gray, 2006; Lambert et al., 1985). Like for grass biomass, if livestock are dispersed around the paddock this may help alleviate the build-up of nutrients beneath the trees, and the particularly high levels of nitrate-N and Olsen-P in the soil.

Total-N and total-P losses in the open pasture treatment (total-N: 0.3 kg ha^{-1} yr^{-1}, total-P: 0.1 kg ha^{-1} yr^{-1}) were on the lower side of the range for catchment studies reviewed by McDowell and Wilcock (2008). Nevertheless, despite open pasture having greatly reduced soil fertility and poorer pasture conditions, nutrient concentrations in open pasture surface runoff were of the same order of magnitude as in kānuka pasture. Therefore, the reason for the 10–100 times greater nutrient loads in kānuka pasture was due to the greater surface runoff volumes. Therefore, this adds weight to the argument that interventions aiming to reduce nutrient losses must be focused on surface runoff mitigation, and nutrient losses may still be high in poor condition pastures that experience high surface runoff.

5.4.4 Limitations

Complexity of agricultural areas (in New Zealand and internationally) in terms of climate, topography, soil type, grazing intensity and livestock type means extrapolating these results past this farm is difficult, as surface runoff and sediment and nutrient losses will most likely vary with these factors. Measuring surface runoff and sediment and nutrient losses between paired areas of pasture with and without silvopastoral trees in other agricultural areas, domestically and internationally, is essential to understand if these results are a wide-spread occurrence.

Despite being replicates, there was variation in terms of the number of trees in the kānuka pasture plots; plot 1 and plot 2 had three kānuka trees but plot 3 had two trees. This would have influenced rainfall interception and throughfall, as well as VSM. Nevertheless, each kānuka pasture plot had similar amounts of average surface runoff per event (2.8 mm in plot 1, 1.7 mm in plot 2 and 2.5 mm in plot 3). This suggests that rainfall interception and soil moisture were having less influence on surface runoff processes than other factors, which was the conclusion in this study with reduced grass biomass most likely influencing surface runoff processes. Nonetheless, this point highlights the difficultly of working with silvopastoral trees that have formed without tree management (e.g. planted at specific densities, felling unneeded trees). More research is required on more standardised plots that have been planted at specific densities.

Finally, within the study paddock, there were areas under some trees where livestock tended to gather which suppressed grass cover (livestock camping areas). This is generally the case in current hill country kānuka silvopastoral systems as tree densities are often low which exaggerates the environmental differences between tree and treeless pastoral environments. As trees were chosen in this study that did not have obvious livestock camping areas, the results of this study cannot even be generalised for kānuka trees within this paddock. This again highlights the complexity of these systems when quantifying surface runoff and sediment and nutrient losses. This study stresses the importance of more comparative research on these losses in silvopastoral systems with paired open pasture environments to better inform the use of silvopastoral systems as a tool for reducing agricultural losses.

5.5 Final Considerations

5.5.1 Conclusions

Surface runoff was significantly greater in kānuka pasture compared to open pasture per rainfall event, and the cumulative surface runoff over the year was over seven times greater in kānuka pasture. All sediment and nutrient (N and P) loads were 10–100 times greater in kānuka pasture compared to open pasture and were a function of increasing surface runoff.

The increase in surface runoff beneath the trees is contrary to past agroforestry research, despite kānuka pasture having elevated soil fertility and improved soil structure (in terms of porosity and organic matter). The likely reason for the increased surface runoff beneath the kānuka trees was the reduced grass biomass decreasing the amount of grass present as a physical barrier to slow surface runoff movement, allowing more water to infiltrate into the soil. Livestock are the most likely reason for this, preferentially grazing the pasture beneath the trees because of the more desirable pasture species (perennial ryegrass and cocksfoot), or the provision of shade. These results suggest that vegetation variables can exhibit a greater influence on surface runoff processes than soil conditions in certain situations. Stemflow may have also been contributing to surface runoff and further work is required to understand stemflow in New Zealand hill country silvopastoral trees.

The elevated soil fertility under kānuka is in accordance with the elevated concentrations of total-N, nitrate-N, total-P and DRP in kānuka pasture surface runoff. The increased sediment and nutrient loads in this treatment are most likely due to livestock concentrating nutrients beneath the kānuka trees and facilitating nutrient transfer to these areas. Nevertheless, if the same amount of water had been lost in open pasture via surface runoff, nutrient loads would have been the same order of magnitude as in kānuka pasture.

An encouraging result from the study is the minimal surface runoff and sediment and nutrient losses in open pasture, most likely due to the standing grass biomass in open pasture. Despite there being evidence of open pasture having lower fertility and poor pasture condition, these results suggest that maintaining grass biomass on hill slopes can be used to reduce surface runoff and thus sediment and nutrient loads, even if soil conditions are poor.

If livestock behaviour was the key reason for the increased surface runoff and sediment and nutrient loads beneath the trees, dispersing livestock to different areas of the paddock, or treating the environments as separate management units, may help alleviate these issues. One possible option would be to eliminate the choice between a good pasture condition sheltered environment and a poor pasture condition unsheltered environment by planting trees in open pasture areas.

5.5.2 Wider implications

These results are different to how silvopastoral systems have impacted agricultural losses when compared to other agricultural practices or native forest in past studies, and highlights that current silvopastoral knowledge should not be assumed for all land-use comparisons. The results challenge the prevailing knowledge of silvopastoral system benefits for reducing agricultural system losses and shows that the addition of kānuka silvopastoral trees may have negative implications for surface runoff and sediment and nutrient losses in agricultural areas. It shows that silvopastoral trees will not be a panacea in all agricultural areas, and that they will need to be managed accordingly as per the specific system needs. In the case of New Zealand hill country, removing the choice for livestock between a shaded and unshaded area may reduce the losses that were measured under the trees.

This study highlights that the environment in an agricultural system can function very differently in terms of surface runoff and sediment and nutrient losses, even if they are less than 20 m away from each other. It shows that the scale of this type of research is very important and having paddock or catchment scale studies is not necessarily sufficient for understanding agricultural system losses. Plot scale studies of within-paddock features are required to understand which are the primary sources of water, sediment and nutrient losses. These critical source areas can then be targeted for mitigation.

This study gives evidence that silvopastoral trees can influence livestock activity, which in turn has implications for system losses. It shows that research attempting to understand how silvopastoral systems impact agricultural losses must address how the trees influence livestock activity, something this study did not specifically measure. Integrating livestock activity research with agricultural system loss research is an important consideration for future studies. Moreover, studies that measure surface runoff and sediment and nutrient losses under silvopastoral systems which control for grazing will be highly informative.

Nevertheless, these losses must be considered against the potential benefits of adding trees to pastoral land, especially areas that are highly susceptible to erosion. Tree co-benefits will include carbon sequestration, livestock health and welfare, biodiversity conservation and slope stability (Dominati et al., 2019; Mackay-Smith et al., 2021). Even if in certain situations trees increase surface runoff or sediment and nutrient losses compared to open pasture, the trees will help prevent mass movements events (Spiekermann et al., 2021), which could generate considerably more sediment loss than sheet erosion over the long-run.

As far as we are aware, this is the first study (domestically or internationally) to measure the impact of a silvopastoral system on surface runoff and associated sediment and nutrient losses in areas of equivalent pasture with and without fully-grown silvopastoral trees. More studies with this comparison are required under different topographies, soil types, grazing regimes and climates, and with different tree designs, densities and species, to form more generalised conclusions for the viability of silvopastoral systems for mitigating agricultural losses in pastoral areas.

Chapter 5 summary

This chapter explored hypothesis 3 and measured the impact of a kānuka silvopastoral system on one of the most important current environmental challenges in New Zealand hill country: surface runoff and sediment and nutrient losses. The study found surface runoff and sediment and nutrient losses to be 10-100 times greater in kānuka pasture plots, and sediment and nutrient losses were associated with increased surface runoff. This result was contrary to what was hypothesised, and was likely because of livestock preferentially grazing the pasture under the trees, and increasing the amount of surface runoff in these plots. These results are likely a result of the tree configuration, having a few isolated clumps of trees surrounded by large areas of open pasture. Changing the tree configuration by planting more trees and removing a choice for livestock between more productive tree pasture areas and less productive open pasture environments could help mitigate this issue.

Chapter 6 General discussion

This is the final chapter of the thesis that is a general discussion which synthesises the results of all chapters and links the main findings together. This chapter also identifies the key novel findings in the research and puts these conclusions into a wider context within New Zealand silvopastoralism, answering the overarching aim of the thesis. Finally, it suggests important future research that is needed to thoroughly assess the potential of kānuka more fully as a silvopastoral tree in New Zealand hill country.

This chapter is not for publication.

6.1 Overall findings

The overarching aim of this thesis is to inform change in New Zealand hill country, to unlock opportunities for silvopastoral trees to provide production and environmental benefits to New Zealand farms, thus overcoming production and environmental trade-offs. The thesis explored this aim by presenting a framework that showed the full range of known silvopastoral outcomes, and within this framework, reviewed the potential positive impact to hill country of a kānuka (*Kunzea* spp.) silvopastoral system compared to a poplar (*Populus* spp.) silvopastoral system. The research chapters then investigated the following hypotheses:

1) **Kānuka silvopastoral trees positively influence pasture production compared to open pasture in New Zealand hill country by increasing the availability of water and nutrients.**
2) **Kānuka silvopastoral trees increase the growth of more productive pasture functional groups under its canopy, and at least maintain pasture stability compared to open pasture in New Zealand hill country.**
3) **Kānuka silvopastoral trees reduce surface runoff and sediment and nutrient losses compared to open pasture in New Zealand hill country.**

The framework in Chapter 2 showed that a kānuka silvopastoral system may have many potential positive outcomes compared to a poplar silvopastoral system in terms of pasture production, the longevity of the trees and their management, biodiversity conservation, carbon sequestration, livestock welfare, cultural values and additional farm income besides livestock production. These benefits are primarily because the tree is a native, which means kānuka should be better adapted to local hill country conditions and a better habitat to local fauna, in addition to its evergreen nature, and its smaller size compared to poplar, which should reduce wind damage and increase the longevity of the tree. Nevertheless, there are trade-offs associated with establishing a tree like kānuka, as it grows more slowly than poplar and would have to be established as a seedling or small tree and protected from livestock.

Kānuka as a silvopastoral tree can also positively influence pasture production outcomes in New Zealand hill country compared to adjacent open pasture positions. There was 107.9% more pasture production recorded in kānuka pasture positions compared to open pasture positions at two sites over two years. Olsen-phosphorus, potassium, sodium and magnesium, and porosity were all significantly greater under the trees, but soil moisture was similar under and away from the trees (year-round). Olsen-phosphorus, porosity and potassium best explained the variation between kānuka pasture and open pasture positions. The improvements in soil condition under the trees is hypothesised to be because of livestock depositing nutrients and organic matter in the tree pasture environment, in addition to the trees adding organic matter to the soil via litterfall. Nevertheless, more research is required to confirm these findings on other farms and in other hill country situations.

Kānuka silvopastoral trees increased pasture production by facilitating the growth of fast-growing competitor functional groups by the mass ratio hypothesis such as perennial ryegrass (*Lolilum perenne*), cocksfoot (*Dactylis glomerata*) and high fertility annuals: soft brome (*Bromus hordeaceus*) and barley grass (*Critesion murinum*). Browntop (*Agrostis capillaris*), medium fertility species (sweet vernal (*Anthoxanthum odoratum*)) and low fertility tolerant grasses (Danthonia (*Rytidosperma* spp.) and vulpia hairgrass (*Vulpia bromoides*)) were most strongly positively associated with the poorer soil conditions of open pasture. Species diversity (Shannon diversity, species richness and species evenness) and functional richness were significantly less under the trees, but functional evenness and functional dispersion were similar between kānuka pasture and open pasture. Moreover, because the functional groups that were promoted in kānuka pasture had a range of survival strategies (mixed and annual survival strategies), this is evidence that pasture stability was maintained in kānuka pasture compared to open pasture.

Annual surface runoff was 53.8 mm in kānuka pasture and 7.5 mm in open pasture, despite kānuka pasture having improved soil conditions. This result is contrary to what was expected, and past silvopastoral research, with no past studies finding increased surface runoff under silvopastoral trees compared to agricultural land (de Aguiar et al., 2010; Grewal et al., 1994; Hussain, 2009) . Kānuka pasture had species indicative of good pasture condition (López et al., 2006), even though the plots had significantly less standing grass biomass. This was most likely due to livestock preferentially grazing the pasture under kānuka which led to less attenuation of surface runoff.

Sediment and nutrient losses were 10–100 times greater in kānuka pasture, mainly due to the increase in surface runoff, but also because of livestock concentrating nutrients under the trees through excreta deposition. These results highlight that vegetation impacts can have overriding influences on surface runoff and sediment and nutrient loss processes in silvopastoral systems compared to direct tree facilitation (e.g. litterfall and microclimate influences) and competition (nutrient and water use). Furthermore, preferential grazing under silvopastoral trees can lead to negative surface runoff and sediment and nutrient loss outcomes.

6.2 Tree spatial designs (configurations and densities) and livestock behaviour

An overriding theme in the results is the influence of livestock in the silvopastoral system. Livestock are likely to have positively impacted the agricultural system in terms of pasture production through excreta deposition in the tree-pasture environment increasing soil nutrient and organic matter levels. Nevertheless, livestock grazing most likely caused the reduced total pasture biomass under the kānuka trees, likely resulting in the greater surface runoff and sediment and nutrient loss in the system at the Wairarapa site.

The tree spatial configuration (also known as tree arrangement (Teklehaimanot et al., 2002)), in terms of how many kānuka silvopastoral trees were in each paddock and their configuration, most likely had a strong influence on livestock behaviour and how livestock interactions impacted the silvopastoral system environment. The kānuka trees growing in New Zealand hill country have generally not been managed in terms of silvopastoralism (Bergin et al., 1995). They are often clumped together with large areas of open pasture in the same paddock (Figure 3.1, Figure 5.1 and Spiekermann et al., 2021). This means livestock often have a choice between tree pasture and open pasture environments when grazing. The hill country regions studied in this thesis can be hot and windy (Section 3.3.2), which mean the sheltered kānuka pasture environment is most likely highly favourable to livestock in summer and winter.

The livestock behaviour under the trees is likely creating a positive feedback loop in the kānuka tree environment. The shade and shelter attract livestock in the summer and winter, thus livestock deposit nutrients and organic matter in kānuka pasture. This concentration of resources promotes the growth of fast-growing competitor pasture functional groups (e.g. perennial ryegrass and cocksfoot) (López et al., 2006; Saggar et al., 1990). The growth of these groups will increase the root turnover rate and so continue to build organic matter in the soil (McLaren and Cameron, 1996). Furthermore, the growth of perennial ryegrass and cocksfoot will also likely continue to attract livestock to the tree pasture environment because higher fertility hill country pasture species such as perennial ryegrass have been shown to be preferentially grazed in hill country (López et al., 2003a).

The study highlighted that this agricultural transformation reduced species and functional richness, but pasture stability was not compromised through the growth of functional groups with a range of survival strategies. This indicates that the kānuka trees can improve the production of the agricultural environment whilst not impacting how the pasture responds to stress. Thus, the results give evidence that the production of these hill country pastures can be improved sustainably. As far as I am aware, this study was the first to indicate how, despite silvopastoral systems reducing species and functional richness in this study and in others (Fernández-Moya et al., 2011; López-Carrasco et al., 2015; Marañon, 1986; Rossetti et al., 2015), pasture functionality in terms of stability is not necessarily compromised.

The surface runoff results were, however, contrary to what was hypothesised, and what has been reported in past silvopastoral research (Zhu et al., 2020). All past silvopastoral research has found reduced average surface runoff and associated sediment and nutrient losses under forested canopies or silvopastoral treatments when compared to open pasture treatments (Bambo et al., 2009; de Aguiar et al., 2010; Grewal et al., 1994; Hussain, 2009; López-Díaz et al., 2011; Wiersum, 1985). Past studies have confirmed that a key factor impacting surface runoff and associated sediment and nutrient losses under trees is their influence on understory litter or vegetation (de Aguiar et al., 2010; Wiersum, 1985). Nevertheless, this present study indicates that in silvopastoral systems where livestock are given a choice between open pasture and tree pasture environments, this can lead to increased risk of contaminant losses, most likely due to preferential grazing of herbaceous vegetation under trees.

The evidence of preferential grazing of pasture under the silvopastoral trees because of a choice for livestock between a sheltered tree-pasture environment and unsheltered open-pasture environment suggests that tree configuration is a fundamental consideration in silvopastoralism. Nevertheless, the majority of silvopastoral pasture production research has compared isolated tree and open pasture effects (e.g. Callaway et al., 1991; Douglas et al., 2006; Guevara-Escobar et al., 2007; Marañón and Bartolome, 1994; Moreno, 2008; Seddaiu et al., 2018), different tree densities (e.g. Hawke, 1991; Paciullo et al., 2011; Rozados-Lorenzo et al., 2007), or compared silvopastoral system treatments with an tree-pasture environment and no trees (Kallenbach et al., 2006; Michel et al., 2007; Nair et al., 2007; Rozados-Lorenzo et al., 2007). There has been very little research on the comparison between different silvopastoral tree configurations (Ares et al., 2005; Ares and Brauer, 2005; Paula et al., 2013; Pezzopane et al., 2019; Teklehaimanot et al., 2002;

Tölgyesi et al., 2018). As far as I am aware, only Teklehaimanot et al. (2002) has measured how treatments with varying tree configurations impact silvopastoral production outcomes.

Nevertheless, Teklehaimanot et al. (2002) found no significant differences in pasture and livestock production between open pasture, sycamore trees (*Acer pseudoplatanus* L.) evenly spaced at 100 stems ha^{-1} and 400 stems ha^{-1}, and in clumps at 400 stems ha^{-1}. This was most likely because the trees were only 6 years old in the study, so there may not have been time for livestock to have differing impacts on the system because of tree configuration or tree density variation. Moreover, the amount of open pasture was fairly similar between the sycamore trees that were evenly spaced and in clumps at 400 stems ha^{-1}.

Researching surface runoff and sediment and nutrient losses in a kānuka silvopastoral system with a consistent density throughout a paddock may produce contrasting results to this study (compare Figure 6.1A with Figure 6.1B and Figure 6.1C). If there was a consistent density within a whole paddock, this should result in more even pasture biomass growth as livestock should graze the paddock more evenly as there would only be one type of environment ('tree-pasture environment'). Therefore, farmers would likely be able to control the amount of pasture biomass in the paddock via livestock management as there would not be a choice between good-quality pasture under the trees and poor-quality pasture away from the trees. Thus, surface runoff and contaminant losses could potentially be managed in the silvopastoral system.

By maintaining a consistent density within a paddock and removing 'open-pasture' environments from a paddock, this may also reduce the negative presence of livestock camping spots under some silvopastoral trees (Figure 6.1D). As was explained in Chapters 3, Chapters 4 and Chapters 5, some trees in the paddocks had noticeable livestock camping areas, and other trees had noticeable 'positive' tree effects. The research chapters targeted 'positive' tree effects, so the conclusions are not generalised findings for how kānuka impacts hill country pastures. These livestock camping areas tended to be on the downslope area under the trees (Figure 6.1D). By managing the density and configuration of silvopastoral trees and reducing the amount of open pasture in the paddock, this will most likely help reduce the impact of livestock camping under isolated silvopastoral trees.

Figure 6.1. Different kānuka silvopastoral system configurations. A: Two of the isolated trees studied at the Hawkes Bay site, and the large amount of open pasture in the study paddock. B/C: Examples of more continuous canopy systems that could potentially be used to control the biomass of the grass in kānuka silvopastoral paddocks. D: An example of what is most likely a livestock camping spot on the downslope area of a kānuka tree in a well grazed paddock.

An important question is whether the tree pasture environment would improve if kānuka was planted in a continuous, low-density canopy cover and there was little open pasture in the paddock (Figure 6.1B and Figure 6.1C). As livestock activity would likely be consistent throughout the paddock, if the slope is assumed to be the same in all parts of the paddock and the tree density was low enough to minimise tree-competition, this is where the direct impacts of silvopastoral trees on the agricultural system may have more influence on production outcomes than livestock effects. This could be because of their effects on soil condition and nutrients (litterfall and nutrient enrichment of throughfall) (Callaway et al., 1991; Howlett et al., 2011; Rossetti et al., 2015) and water (reducing evapotranspiration through impacts on shade and wind) (Bahamonde et al., 2009; Joffre and Rambal, 1993; Peri, 2005).

In addition to increased surface runoff and sediment and nutrient losses in kānuka pasture, the soil moisture results were inconsistent with the hypotheses. It was hypothesised that kānuka would increase the availability of soil moisture compared to open pasture because of its potentially reduced water use compared to poplar, and soil moisture facilitation effects in terms of evapotranspiration reductions would be greater than tree water use competition. Nevertheless, there was less soil moisture in the soil under the kānuka trees in the surface runoff plots in Chapter 5. This was likely because of the relatively high tree density within the surface runoff plots. The tree density in the plots was 750 trees ha^{-1} with at least five or six trees influencing soil moisture in the plots, despite the wider paddock area (50 m x 50 m square around the plots) having a density of 68 trees ha^{-1}. Therefore, managing the tree density is important for reducing tree competition for soil moisture.

Nevertheless, soil moisture was also not conserved in kānuka pasture compared to open pasture. Chapter 3 found similar soil moisture between the kānuka pasture and open pasture positions in the topsoil, but Chapter 4 found a negative correlation between soil moisture and total production. Therefore, Chapter 2 overestimated the potential positive impacts of kānuka on soil moisture, and other mechanisms are likely more important for positively impacting pasture production outcomes, such as livestock behaviour or litterfall adding organic matter to the soil.

6.3 Silvopastoral New Zealand hill country implications

The contrasting results between past silvopastoral studies in hill country (Benavides et al., 2009) and this thesis highlights another important theme: that the different bio-physical attributes of kānuka could be leading to improved pasture production outcomes compared to poplar. As far as I am aware, there have been no published studies that have found increased pasture production under mature silvopastoral trees in hill country (Benavides et al., 2009; Devkota et al., 2009; Kemp et al., 2018; Thorrold et al., 1997). Pasture production has been negative compared to open pasture in every published study under the most commonly planted silvopastoral tree in hill country, poplar (Benavides et al., 2009). Moreover, the one study that has measured pasture production under willow (*Salix* spp.) found 40% reduction in pasture production under tree canopies (Miller et al., 1996), and no published study on radiata pine (*Pinus radiata* D. Don) ≥ 15 years old has found greater pasture production under their canopies in New Zealand (Benavides et al., 2009). Considering trees with different tree attributes to poplar, willow and radiata pine will be integral for optimising pasture production in New Zealand hill country silvopastoral systems.

Nevertheless, there were many limitations with both these studies, such as the tree influences could be due to site specific factors, there was evidence that livestock activity had compounding impacts on the tree-pasture environment, and the studies did not confirm whether pasture production increased on a net basis within the paddock. Therefore, more research is required to overcome these limitations and confirm the potential of kānuka as a silvopastoral tree in New Zealand. However, because this is the first published study in New Zealand to show a measured increase in pasture production under silvopastoral trees compared to adjacent open pasture positions, if these results can be confirmed on other farms, kānuka could be transformative to New Zealand hill country agriculture.

Bertness and Callaway (1994) hypothesised that plant facilitative effects increase at greater abiotic stresses and consumer pressures (abiotic stress hypothesis) (Figure 6.2). The authors suggest that competition would predominate when resources were less limiting and consumer pressure was low or moderate. Yet in more stressful conditions, it is a better strategy for plants to ameliorate the stress of other plants than to compete for the limiting resources (Bertness, 1991; Callaway, 2007). In silvopastoral systems, Ratliff et al. (1991) found evidence of this for production outcomes under blue oak (*Quercus douglasii* Hook. & Arn.) trees, with facilitation (increased pasture production under the tree canopy) occurring at lower production levels and competition (reduced pasture production under the tree canopy) occurring at higher production levels. However, Moreno (2008) did not find evidence of this hypothesis for pasture production in different fertilisation and irrigation treatments under holm oak (*Quercus ilex* L.) trees at three sites with different rainfall. This study did not test pasture production outcomes across a climate gradient, as rainfall was similar at the Wairarapa and Hawkes Bay site. Nevertheless, the impact of kānuka on production outcomes could be different in different climates.

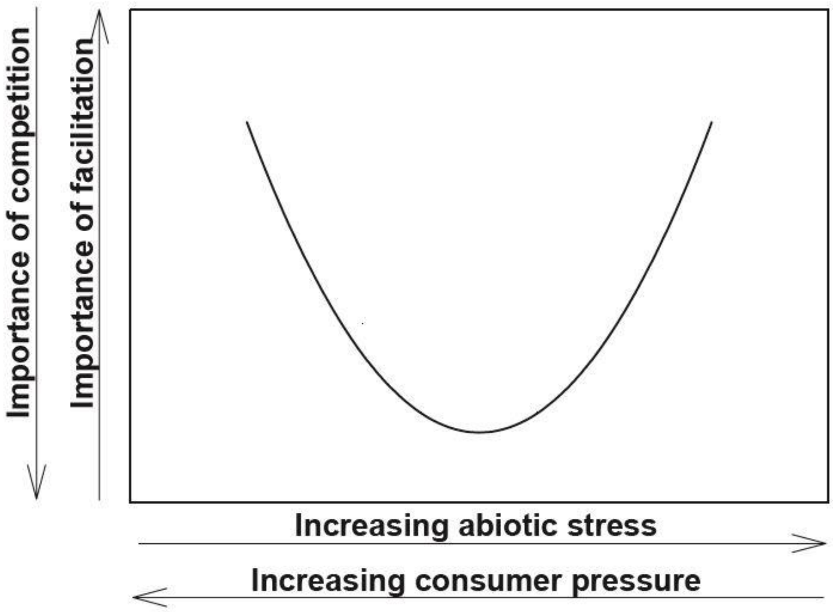

Figure 6.2. Conceptual model for how competition and facilitation varies in plants with increasing abiotic stress and consumer pressure (abiotic stress hypothesis). Figure reprinted from (Callaway, 2007) (Copyright © Springer Nature 2007), which was redrawn from (Bertness and Callaway, 1994) (Copyright © Elsevier LTD. 1994).

The framework presented in Chapter 2 highlights the holistic nature of silvopastoral systems and their many outcomes in New Zealand hill country (Figure 2.1). Traditionally, trees have primarily been valued on their potential to stabilise slopes. Fast-growing trees with large root systems that can be established easily in the presence of grazing livestock has been the basis for silvopastoral tree selection. The framework shows how these tree attributes are linked to other silvopastoral outcomes, and this framework, in addition to Chapter 2, provides evidence that they may negatively impact some outcomes such as pasture production, longevity, biodiversity value and carbon sequestration potential compared to a kānuka silvopastoral system. Therefore, this thesis suggests that selecting trees with different attributes to poplar could lead to improvements in less researched silvopastoral outcomes. Acknowledging the linkages between tree attributes and a wide range of silvopastoral outcomes will be fundamental for comparing the full range of benefits and costs of a specific silvopastoral tree, and making informed planting decisions.

The framework is an opportunity for researchers, farmers and land managers in New Zealand to see the full range of potential outcomes of silvopastoral systems in hill country. Additionally, despite the limitations, chapter 3 gives evidence that pasture production can be greater under silvopastoral trees compared to adjacent open pasture positions in some situations in hill country. In terms of livestock production, the provision of shade and shelter has been shown to increase livestock grazing time (Betteridge et al., 2012; Mitlöhner et al., 2001), increase livestock growth (Gaughan et al., 2010; Mitlöhner et al., 2002, 2001; Olivares and Caro, 1998) and reduce livestock mortality (Pollard, 2006). Additionally, the provision of shade will have livestock welfare implications due to mortality and heat stress reductions (Blackshaw and Blackshaw, 1994; Pollard, 2006).

Furthermore, as was identified in the framework (Figure 2.1), a kānuka silvopastoral system could have important additional environmental benefits in terms of carbon sequestration (both the biomass growth of the tree and impacts to soil organic matter) and biodiversity conservation. The potential increased surface runoff and sediment and nutrient losses could be an environmental cost to a kānuka silvopastoral system, however, this was most likely a result of the tree configuration that can be managed. Kānuka is also a native and so likely has cultural significance (Chapter 2), and a native silvopastoral system could be an excellent opportunity to increase the range of a culturally significant tree and the habitat of native birds (Dominati et al., 2019; Peri et al., 2016a; Williams and Karl, 2002). Finally, the greater longevity of kānuka compared to poplar mean any benefits to the system could last for at least 100 years. These reasons indicate that a kānuka silvopastoral system could have the potential to be a transformative multifunctional land management practice that provides a range of intergenerational services to agricultural land. Nevertheless, more research is required to confirm this potential

There is a growing need in New Zealand for transformative land management practices to overcome New Zealand's current environmental challenges, such as climate change, water quality issues, and biodiversity and soil conservation. However, it is fundamental that land management practices attempting to provide environmental and cultural benefits to farms do not significantly impact the farm business, ensuring that they remain profitable. If they do not, the cost of uneconomic environmental practices could result in other unintended social consequences (Bjørn, 2020; Hazlitt, 1988; Shellenberger, 2020; Sowell, 2004), such as inflation (Hazlitt, 1988) or stagflation (Bjørn, 2020). Therefore, land management practices that overcome production and environmental trade-offs will be integral for resulting in an overall positive impact to society (Bjørn, 2020; Shellenberger, 2020). If more research can confirm that kānuka does provide positive benefits to production in hill country on a net basis, kānuka silvopastoral systems could be an important land management practice in this regard.

A cost, however, to planting a native like kānuka is difficulties during establishment (as highlighted in Chapter 2). In hill country, planting poplar as sharpened, coppiced poles that can be established in the presence of grazing livestock has been integral to their adoption as soil conservation trees (Charlton et al., 2007; Wilkinson, 1999). With current technology, planting kānuka will not cost more than poplar in terms of planting and protection material, but it will take more time to plant and protect the seedlings (on-going research). Moreover, it will be longer for the trees to establish and have an influence on the silvopastoral system, due to the slower growth rate of kānuka compared to poplar (Boffa Miskell Limited, 2017; Marden and Phillips, 2013; McIvor et al., 2011).

Nevertheless, these costs must be compared against the overall benefits of the trees, over the whole of its life. Slower growing trees that potentially have a facilitative relationship with pasture production, should provide substantially more benefits over its lifespan compared to a tree such as poplar, where the recommended practice is to fell and replant after 40 years (Charlton et al., 2007). Moreover, the management of kānuka will likely be less than poplar when the trees are mature (Chapter 2). If the intergenerational benefits of a slower-growing native tree such as kānuka can be shown, it could be worth the extra costs associated with establishment. Moreover, if demand for planting kānuka seedlings increased, the technology for planting the trees and protecting the seedlings and young trees will most likely improve. Finally, alternative establishment options might be sought, such as thinning higher density stands that have already naturally regenerated (Spiekermann et al., 2021), or removing grazing iteratively from paddocks, and allowing some seedlings to naturally germinate and protecting those that grow at the required density.

6.4 Market incentives and land use change

Innovations that add environmental *and* economic value to society, will be key to solving future environmental challenges. As an example of how market innovations have positively impacted environmental issues in the past, up until the 19th century, ivory and tortoiseshells used to be irreplaceable and highly valuable materials because of their plasticity (Arts, 1840; Shellenberger, 2020). However, the invention of celluloid from cotton led to the wide-scale use of plastics and meant demand for both elephant (Elephantidae) and sea turtles plummeted because plastic was a superior product and cheaper than ivory and tortoiseshell (Shellenberger, 2020).

Moreover, whales also used to be highly sought after because of the many resources you can acquire from them, but principally oil, which was favoured as a burning material for light over candle and wood (Davis et al., 1997). In the 19th century, distilled petroleum started to be used as a lighting fluid, and because the cost of petroleum was much less than whale oil, industry change was dramatic (Shellenberger, 2020).

These environmental issues were solved by innovation. A cheaper alternative was created, which meant market incentives caused the dramatic reduction in demand for tortoiseshells, ivory and whale oil. Although plastic and oil are contentious products now, due to market processes, they were vital solutions to environmental issues in the 19th century (Shellenberger, 2020).

Market processes also incentivise land use change. As an example, the area of forestry plantations in New Zealand has increased by 28.9% from 1990 to 2015 (AgFirst NZ, 2017), primarily driven by the low profitability of some areas of hill country and/or the emissions trading scheme and carbon farming (AgFirst NZ, 2017; Ministry for Primary Industries, 2020). Finding silvopastoral systems which provide a range of environmental services and are superior from a production perspective, will incentivise the use of silvopastoral systems and increase environmental value on farms.

If the positive impacts of kānuka on pasture production and pasture botanical composition can be confirmed in other studies, this system could provide a market incentive to farmers for tree planting, and act as an investment to the pastoral part of the business. If silvopastoral trees can also be shown to increase livestock production by the provision of shade and shelter, this will likely add further economic value to farms.

6.5 Future research and concluding remarks

Because of the potential of kānuka to provide multifunctional benefits to New Zealand's agricultural landscapes, more research is required to validate the results of this thesis in different climatic regions and tree designs, and to provide generalised conclusions as to the effects of kānuka on the local agricultural environment. Future research topics include:

1) Pasture and livestock production outcomes in different kānuka silvopastoral tree designs (densities and configurations) and climates.
2) Livestock behaviour in different silvopastoral tree designs and its relation to soil fertility.
3) Surface runoff and sediment and nutrient losses where livestock grazing and the biomass of grass under and away from the silvopastoral trees is controlled.
4) The establishment of kānuka:
    a. Can the current protection method for establishing kānuka seedlings be improved?
    b. How does establishing kānuka as individual seedlings or small trees compare to thinning high density patches, or removing grazing and allowing some seedlings to naturally germinated and protecting those growing at the required density?
5) The biophysical mechanism for how kānuka impacts the agricultural environment:
    a. Kānuka water use, stemflow and a system water balance compared to open pasture.
    b. Wind reductions in a kānuka silvopastoral system compared to open pasture.
    c. The impact of kānuka on temperature in different climates compared to open pasture.
    d. Soil fauna and mycorrhizal functioning under kānuka trees compared to open pasture.
    e. Nutrient enrichment of throughfall, and carbon and nitrogen cycling of litterfall in kānuka silvopastoral systems.

This thesis is the first study to show that in certain situations pasture production can be greater under fully mature silvopastoral compared to open pasture in New Zealand. Since market incentives can rapidly change behaviour and land-use, this result could be ground-breaking for

New Zealand hill country management because of the potential economic incentivisation of tree planting. Nevertheless, more research is required to confirm this potential on other farms and on a net basis within paddocks. Furthermore, many other aspects of the system must explored, as shown above, to provide a full evaluation of kānuka silvopastoral systems.

The surface runoff and sediment and nutrient loss results were contrary to what was expected, but were complementary to the results of Chapter 3 and 4, indicating that livestock were preferentially grazing the pasture under the kānuka trees and spending more time in the tree-pasture positions. Measuring surface runoff and sediment and nutrient losses under silvopastoral trees with a continuous canopy will be important for learning whether this increase in surface runoff and sediment and nutrient loss in a function of tree configuration, and thus can be mitigated by planting more trees within paddocks.

This thesis opens the door for continued work on silvopastoral trees that have a potentially positive impact on pasture production. If more research shows that silvopastoral trees can add economic value to hill country farms, this will confirm whether silvopastoral trees can overcome economic and environmental trade-offs in New Zealand hill country.

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Appendix A List of publications and presentations

A.1 Peer-reviewed journals

Mackay-Smith, T.H., Burkitt, L.L., López, I.F., Reid, J.I., 2022. The impact of a kānuka silvopastoral system on surface runoff and sediment and nutrient losses in New Zealand hill country. CATENA 213, 106215. https://doi.org/10.1016/j.catena.2022.106215.

Mackay-Smith, T. H., Burkitt, L., Reid, J., López, I. F., & Phillips, C. (2021). A Framework for Reviewing Silvopastoralism: A New Zealand Hill Country Case Study. Land, 10, 1386. https://doi.org/10.3390/land10121386.

Mackay-Smith, T.H., López, I.F., Burkitt, L.L., Reid, J.I., 2022. Kānuka Trees Facilitate Pasture Production Increases in New Zealand Hill Country. Agronomy 12, 1701. https://doi.org/10.3390/agronomy12071701

Mackay-Smith, T., López, I. F., Burkitt, L. L., & Reid, J. I. (2023). Pasture production-diversity relationships in a kānuka silvopastoral system. *Ecological Solutions and Evidence*. Accepted.

A.2 Conference presentations

Only one conference was attended because of COVID-19 related conference cancellations.

Mackay-Smith, T.H., Burkitt, L.L., López, I.F., Reid, J., 2022. Kānuka as a silvopastoral tree for low producing hill country, in: Christen D.J., Horne, D.J., Singh, R. (Eds.), Occasional Report No. 34. Presented at the Adaptive Strategies for Future Farming, Farmed Landscapes Research Centre, Massey University, Palmerston North, New Zealand.

Appendix B DRC 16 forms

DRC 16

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
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:	Thomas H. Mackay-Smith
Name/title of Primary Supervisor:	Lucy L. Burkitt
In which chapter is the manuscript /published work:	Chapter 2

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Mackay-Smith, T. H., Burkitt, L., Reid, J., López, I. F., & Phillips, C. (2021). A Framework for Reviewing Silvopastoralism: A New Zealand Hill Country Case Study. Land, 10(12), 1386. https://doi.org/10.3390/land10121386.

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

Land

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Tom formulated the review idea, created the framework and did the literature search.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Thomas Mackay-Smith Digitally signed by Thomas Mackay-Smith Date: 2022.04.26 17:19:29 +12'00'
Date:	26-Apr-2022
Primary Supervisor's Signature:	Lucy Burkitt
Date:	26-Apr-2022

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

GRS Version 5 – 13 December 2019
DRC 19/09/10

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TE KUNENGA KI PŪREHUROA
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:	Thomas H. Mackay-Smith
Name/title of Primary Supervisor:	Lucy L. Burkitt
In which chapter is the manuscript /published work:	Chapter 3

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Mackay-Smith, T.H., López, I.F., Burkitt, L.L., Reid, J.I., 2022. Kānuka Trees Facilitate Pasture Production Increases in New Zealand Hill Country. Agronomy 12, 1701. https://doi.org/10.3390/agronomy12071701

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

Agronomy

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Tom helped formulate the paper concept, undertook all the fieldwork, did the data analysis and wrote the paper.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Thomas Mackay-Smith Digitally signed by Thomas Mackay-Smith Date: 2023.02.24 13:46:38 +13'00'
Date:	24-Feb-2023
Primary Supervisor's Signature:	Lucy Burkitt Digitally signed by Lucy Burkitt DN: cn=Lucy Burkitt, c=NZ, o=Massey University, ou=Farmed Landscapes Research Centre, email=L.Burkitt@massey.ac.nz Date: 2023.02.27 09:54:05 +13'00'
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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:	Thomas H. Mackay-Smith
Name/title of Primary Supervisor:	Lucy L. Burkitt
In which chapter is the manuscript /published work:	Chapter 4

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Mackay-Smith, T., López, I. F., Burkitt, L. L., & Reid, J. I. (2023). Pasture production-diversity relationships in a kānuka silvopastoral system. Ecological Solutions and Evidence. Accepted.

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

Ecological Solutions and Evidence

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

Tom helped formulate the paper concept, undertook all the fieldwork, did the data analysis and wrote the paper.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Thomas Mackay-Smith Digitally signed by Thomas Mackay-Smith Date: 2023.02.24 13:47:48 +13'00'
Date:	24-Feb-2023
Primary Supervisor's Signature:	Lucy Burkitt Digitally signed by Lucy Burkitt DN: cn=Lucy Burkitt, c=NZ, o=Massey University, ou=Farmed Landscapes Research Centre, email=L.Burkitt@massey.ac.nz Date: 2023.02.27 09:54:30 +13'00'
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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:	Thomas H. Mackay-Smith
Name/title of Primary Supervisor:	Lucy L. Burkitt

In which chapter is the manuscript /published work: Chapter 5

Please select one of the following three options:

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Mackay-Smith, T.H., Burkitt, L.L., López, I.F., Reid, J.I., 2022. The impact of a kānuka silvopastoral system on surface runoff and sediment and nutrient losses in New Zealand hill country. CATENA 213, 106215. https://doi.org/10.1016/j.catena.2022.106215.

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- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

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Candidate's Signature:	Thomas Mackay-Smith (Digitally signed by Thomas Mackay-Smith Date: 2022.04.26 17:23:49 +12'00')
Date:	26-Apr-2022
Primary Supervisor's Signature:	Lucy Burkitt
Date:	26-Apr-2022

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