THE EFFECT OF INTERCROPPING ON THE YIELD AND QUALITY OF FORAGE OATS AND PEAS

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THE EFFECT OF INTERCROPPING ON THE YIELD AND QUALITY OF FORAGE OATS AND PEAS

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Abstract

Cereal-legume intercrops have the potential to improve dry matter yield and quality of forage. A study was conducted at Massey University in Palmerston North, New Zealand in 2020, to determine the effect of intercropping on the yield and quality of forage oats (*Avena sativa* L.) and peas (*Pisum sativum* L.). Oats and peas were sown in the oat: pea ratios; 100:0, 75:25, 50:50, 25:75 and 0:100. The sowing rates of 100% oats and peas were 150kg and 250kg ha^{-1} respectively, from which seed rates for mixtures were calculated. Two harvests were taken, the boot (harvest 1) and milky dough stage (harvest 2) of oats and the dry matter yield and forage quality traits including crude protein (CP), Acid Detergent Fiber (ADF), Neutral Detergent Fiber (NDF) and metabolisable energy (ME) were determined.

The sowing ratios significantly (P=0.05) affected the dry matter yield of forage at both harvests. At harvest 1, the sole cropped peas produced a significantly lower yield (5930 ha^{-1}) compared to the other treatments which were similar, producing yields that ranged from 14083kg ha^{-1} to 15823kg ha^{-1}. At harvest 2, the 25% oat:75% pea treatment mixture had a significantly higher yield (21110kg ha^{-1}) than the sole cropped unfertilised*l* oats (14353kg ha^{-1}), while the rest of the treatments were not significantly different from each other and produced yields ranging from 14885kg ha^{-1} to 16690kg ha^{-1}.

All forage quality parameters were significantly affected by sowing ratios at harvest 1 while at harvest 2 only the CP and NDF were significantly influenced by sowing ratios. At harvest 1, the CP content was significantly (P=0.05) higher in the sole cropped peas and mixtures compared to sole cropped oats and ranged from 13.24-17.45% while the ME was only significantly higher in the sole cropped peas. Sole cropped peas and mixtures also had significantly lower ADF and NDF levels compared to sole cropped oats. At harvest 2, only the 25% oat:75% pea mixture had significantly higher CP content (8.81%) content compared to sole cropped unfertilised oats (5.02%). Intercropping evaluation indices showed that all three mixtures had a yield advantage as mixtures produced land equivalent ratios of 1.06, 1.12, and 1.26 for the 50:50, 75:25, and 25:75 oat: pea ratios respectively. The plant height and leaf area index in this study were not significantly affected by sowing ratios at both harvests.

Intercropping significantly improved the quality of forage harvested at the boot stage of oats, by increasing the CP and lowering the ADF and NDF content, improving palatability and digestibility of the forage. Land equivalent ratios of greater than 1 showed that intercropping produced greater yield per unit area compared to monoculture. Intercropping with peas can be used by farmers in the Manawatū area to improve the quality of oats grown for silage, the optimum seed ratio being 25% oat:75% peas.

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List of Abbreviations

ADF	Acid detergent fibre
℃	Degrees Celsius
Cm	Centimetre
CP	Crude protein
DM	Dry matter
FAO	Food and Agriculture Organisation
Kg	Kilogram
LAI	Leaf area index
LER	Land equivalent ratio
ME	Metabolisable energy
MJ	Megajoules
NDF	Neutral detergent fibre
NZD	New Zealand dollars
T/ha	Tonnes per hectare
UK	United Kingdom
USA	United States of America

Chapter 1 : General introduction

In the last 50 years, global food production has tripled due to improvements in agricultural practices and technology and expansion of agricultural land, sufficiently providing for a growing global population (FAO, 2017; Sonnino, 2015). This increase in production, however, comes at a great cost to the environment (FAO, 2017). Expanding land for agriculture results in the destruction of forests which destroys habitats, results in loss of species, and erodes biodiversity. Furthermore, agriculture substantially contributes to greenhouse emissions and results in the depletion and contamination of groundwater (FAO, 2017; Sonnino, 2015).

With time, changes in diet and emerging overconsumption patterns have put pressure on food production systems, further threatening the environment(FAO, 2017). This pressure is magnified by a growing population, projected to reach 9 billion by mid-century(FAO, 2017; McCalla, 2001). This population growth will lead to an increase in the demand for food and other agricultural products, projected to increase by 50% from 2012 to 2050 (FAO, 2017; Tabaglio, Ganimede, & Bertoni, 2015). Eroding of natural resources coupled with population growth on static land endangers the sustainability of food production systems and reduces the capacity of the world to meet its future food needs (FAO, 2017; McCalla, 2001; Tabaglio et al., 2015). As the global population has increased, the cropland area per capita has declined resulting in a world average decline of 17% in 2019 (FAOSTAT, 2021). The key to feeding future generations on limited static land is increasing the output per unit area (Gebru, 2015). There is, therefore, a need to promote agricultural systems that have higher conversion efficiencies (FAO, 2017; Sonnino, 2015). These are systems that produce more while consuming fewer natural resources and that increase the output per unit area (FAO, 2017; Gebru, 2015; Sonnino, 2015). Such systems are an integral determinant in the world's ability to feed itself in the future.

Intercropping has the potential to improve the sustainability of agricultural production systems by increasing the output per unit area, improving soil health, reducing the incidence of pests and disease, and improving the stability of yields (Begna et al., 2011; Bybee-Finley & Ryan, 2018; Eskandari & Ghanbari, 2009). Intercropping is defined as “ the growing together of two or more crops on the same area of land at the same time” (Willey, 1990). In intercropping systems, an increase in output is either a result of an increase in resource capture or an increase in resource utilisation efficiency (Willey, 1990).

In forage crop production, the intercropping of cereals and legumes is a cultivation technique that has been used for a long time around the world. Cereal-legume intercrops are very important as they provide a balance between forage yield and quality (Eskandari, 2012; Osman & Nersoyan, 1986). This is a result of combining high quality, but low yielding legumes, with low quality, but high yielding cereals (Eskandari, 2012; Lithourgidis & Dordas, 2010). The balance in forage yield and quality is a factor of the proportions at which the cereal and legume are sown in the intercrop (Barsila, 2018; Osman & Nersoyan, 1986; Uzun & Ferda, 2012; Willey & Osiru, 1972). Determining the correct sowing ratios of cereals and legumes in an intercrop is therefore very important in improving the yield and quality of forage crops.

New Zealand has an agricultural production and export economy. Dairy and meat production account for 90% of agricultural exports (Robertson, 2010). Its livestock production system is based on grazed pastures which are used in combination with forage crops/conserved feed for periods when pasture supply is low or in areas where facial eczema is high (Matthews, Hodgson, & White, 1999; Newton, 1980; Robertson, 2010). Forage crops can be used as a standing crop for grazing, or they can be processed into hay or silage for future use (Jermyn , Hanson, Scales , & Ryan, 1993). The continued growth of the New Zealand dairy sector will rely on the expansion of pastoral land, increased irrigation, and an increase in forage crop production to support fodder requirements (Robertson, 2010). As such, sustainable production of forage crops is essential in ensuring the maintenance and growth of New Zealand's largest export sector. Intercropping as a management tactic has the potential to help achieve sustainable forage crop production in New Zealand.

A few forage intercropping studies have been conducted in New Zealand, a study was conducted by Shaw, Johnstone, Rogers, and Reid (2009) to determine the optimum sowing time and crop species to be intercropped with maize to increase dry matter production, and Fraser, Knight, Knowles, and Hyslop (2004) investigated the potential of using different cereal-legume combinations planted in between summer harvest and autumn planting to increase annual forage production.

However, no study has been conducted to investigate the effect of intercropping on the yield and quality of oats and peas, two of the main forage crops in New Zealand.

1.1 Objectives of the study

The study was designed to:

a) Determine the effect of intercropping on the dry matter yield of forage oats and peas.
b) Determine the effect of intercropping on forage quality. Specifically, the crude protein, acid detergent fibre, neutral detergent fibre, and metabolisable energy.
c) Evaluate the efficiency of the intercropping system using land equivalent ratios (LER).

1.2 Thesis synthesis and organisation

Chapter 1 introduces the concept of intercropping and highlights its importance in sustainable crop production. This chapter also outlines the study's objectives. Chapter 2 is a survey of literature on the types of intercropping, its advantages and disadvantages, the importance of cereal-legume intercrops, and how their yield and quality are affected by sowing ratios. Chapter 3 outlines the materials and methods used in this study, including the soil and climatic conditions, and field and lab measurements. Chapter 4 presents the findings of this study, which are then discussed in depth in chapter 5. Chapter 6 outlines the conclusions drawn from this study and lists the recommendations for further research on cereal-legume intercropping in New Zealand.

Chapter 2 : Literature review

2.1 Introduction

This chapter presents the survey of literature on intercropping, specifically the types of intercropping, ecological relationships in intercropping, the advantages and disadvantages of intercropping, the importance of cereal-legume forage intercrops, and how the sowing ratios of these intercrops affect the yield and quality of forage.

2.2 Introduction to intercropping

Various definitions have been used to describe intercropping as a crop production method. Intercropping can be defined as “the growing of two or more crops simultaneously on the same area of land where they are simultaneous for a significant part of their growing periods” (Willey, 1979). It can also be defined as “the growing of two or more crops simultaneously such that the period of overlap is long enough to include the vegetative stage” (Gomez & Gomez, 1983).

Intercropping is an ancient agricultural practice that is practiced all over the world (Bybee-Finley & Ryan, 2018; Lithourgidis & Dordas, 2010). It is most commonly practiced by smallholder farmers in low input production systems in Africa and Latin America (Bybee-Finley & Ryan, 2018; Lithourgidis & Dordas, 2010; Maitra et al., 2021). Its use in developed countries is less common and is mainly applied to forage production (Lithourgidis & Dordas, 2010; Maitra et al., 2021).

2.3 Types of intercropping

The different types of intercropping systems are classified based on the arrangement of the crops in the intercrop. They are described below.

2.3.1 Mixed Intercropping

Mixed intercropping is an intercropping system in which crops are grown haphazardly with no distinct row arrangement (Gomez & Gomez, 1983). Though it is advantageous in that it results in relatively higher productivity, its limitation is its labour-intensive nature (Ramert, Lennartsson, & Davies, 2002).

Plate 2.1: A mixed corn and climbing bean intercrop

(Lithourgidis, Dordas, Damalas, & Vlachostergios, 2011)

2.3.2 Row intercropping

Row intercropping is an intercropping system in which at least one of the crops is grown in distinct rows (Gomez & Gomez, 1983; Maitra et al., 2021).

Plate 2.2: Corn and climbing bean row intercropping

(Lithourgidis, Dordas, et al., 2011)

2.3.3 Relay intercropping

Relay intercropping involves the growing of two or more crops together in a field in such a way that only parts of their lifecycle overlap (Bybee-Finley & Ryan, 2018; Gomez & Gomez, 1983). The second crop in relay intercropping is introduced when the first crop has reached its reproductive phase but is not yet ready for harvest (Andrews & Kassam, 1976).

Plate 2.3: Wheat and soybean relay intercropping system

(Jasa, 2003)

In the above relay system, wheat is planted in September, and soybean is planted later, in May. The wheat is then harvested in July, enabling an overlap of the two crops growth cycles (Jasa, 2003)

2.3.4 Strip intercropping

Strip intercropping involves the growing of crops in strips that are sufficiently wide enough to allow separate management practices, but close enough to allow the two crops to influence each other's growth (Ramert et al., 2002).

Plate 2.4: Broomcorn and bush bean strip intercropping

(Lithourgidis, Dordas, et al., 2011)

Row and strip intercropping are favoured in developed countries as they have the greatest potential for mechanisation, whereas mixed cropping is mostly practised in the tropics by smallholder farmers (Ramert et al., 2002).

2.4 Plant density in intercropping systems

Aside from the arrangement of the component crops of an intercropping system, plant density is an important factor in distinguishing intercropping systems and determining the yield (Baldy & Stigter, 1997). Additive and replacement series are two systems distinguished based on the plant density of the intercropping system.

2.4.1 Additive series

An additive series consists of a base/target crop planted at its monocropping planting density with a second crop added to it (Connolly, Goma, & Rahim, 2001; Keating & Carberry, 1993; Maitra et al., 2021).

2.4.2 Replacement series

In a replacement series, component crops are planted at less than their monocropping planting density. In this series, the reduction in crop density of one crop is replaced by the second crop in the intercropping system (Keating & Carberry, 1993; Maitra et al., 2021).

2.5 Ecological relationships in intercropping systems

Different ecological relationships exist in intercropping systems. These relationships are dependent on nutrient availability, soil conditions, climatic conditions, the component crops in the intercrop, and their respective cultivars (Bedoussac et al., 2015; Fukai & Trenbath, 1993). The level at which these ecological relationships occur in an intercropping system determines its overall productivity.

2.5.1 Competition

Competition is a phenomenon in an intercropping system where crop species compete for growth factors such as water, solar radiation, and nutrients (Gomez & Gomez, 1983). Under competition one species modifies the environment in a way that negatively affects the other (Bedoussac et al., 2015). The more similar the component crops are, in terms of architecture and phenology, the higher the competition (Bybee-Finley & Ryan, 2018).

Under intercropping it is common for one crop to grow faster than the other, which often leads it to dominate the other crop (Fukai & Trenbath, 1993; Willey & Osiru, 1972). This dominant crop has higher resource capture, thus limiting the other crop and it is deemed the crop with higher competitive ability in the intercrop (Fukai & Trenbath, 1993; Willey & Osiru, 1972). The competitive abilities of crops are affected by environmental conditions and change based on surplus or scarcity of growth factors (Bedoussac et al., 2015; Fukai & Trenbath, 1993).

2.5.2 Complementarity

Complementarity refers to all positive effects that arise from intercropping (Bybee-Finley & Ryan, 2018). There are two mechanisms through which complementarity occurs, these are resource partitioning and facilitation (Bybee-Finley & Ryan, 2018).

Resource partitioning (also known as niche partitioning/differentiation), is a phenomenon that allows for more efficient utilisation of growth resources when crops are intercropped, as compared to growing them as sole crops (Stomph et al., 2020; Willey, 1990). This occurs when crops occupy different niches in space and time, which reduces the interspecific competition, allowing them to make better use of growth factors (Bedoussac et al., 2015; Bybee-Finley & Ryan, 2018; Stomph et al., 2020; Willey & Osiru, 1972). Selecting crops with differences in rooting depth, vegetative architecture and phenology reduces competition and increases resource partitioning.

Facilitation is a phenomenon where one crop modifies the environment for the benefit of the other crop, or where it provides a limiting resource to the other crop (Bedoussac et al., 2015; Bybee-Finley & Ryan, 2018). An example of facilitation is when a legume provides biologically fixed nitrogen to a cereal, in a cereal-legume intercrop (Bedoussac et al., 2015; Bybee-Finley & Ryan, 2018).

Complementarity in intercropping systems can be either temporal or spatial (Willey, 1990). Temporal complementarity occurs when component crops differ in their peak periods for resource use, whereas spatial complementarity occurs when crops differ in their use of resources as a result of differences in the canopy and root structure/architecture (Willey, 1990). The growing of sorghum and pigeon peas together is an example of temporal complementarity. Sorghum a rapidly growing plant is combined with pigeon pea, whose growth period is up to 4 months longer. In this system, pigeon pea flowers just after sorghum is harvested, resulting in different peak periods for growth factors requirements (Willey et al., 1983). On the other hand, the combination of groundnut and millet is an example of spatial complementarity. The two crops have no differences in growth periods but have differences in root and leaf architecture (Willey et al., 1983). An increase in production under temporal complementarity is due to an increase in resource capture, whereas, under spatial complementarity, an increase in production is attributed to better conversion efficiency of growth factors (Willey et al., 1983).

2.6 Intercropping evaluation indices

Apart from yield, various indices are used to measure the productivity of intercropping systems. Evaluation indices in intercropping are important in characterising and evaluating the different relationships between crops (Filho, Neto, Rezende, Paes Barros, & de Lima, 2015). Indices are used to illustrate the competitive effects, competition intensity, competition outcomes, and economic advantage under intercropping (Neamatollahi, Jahansuz, Mazaheri, & Bannayan, 2013).

2.6.1 Actual yield loss

Actual yield loss is "the proportionate yield loss or gain of intercrops in comparison to the respective sole crop" (Dhima, Lithourgidis, Vasilakoglou, & Dordas, 2007). It can be either positive or negative, indicating yield gain, or yield loss respectively (Neamatollahi et al., 2013).

$AYL = AYL_b + AYL_b$

$AYL_a = [(Y_{ab}/X_{ab})/(Y_a/X_a)] - 1$

$AYL_b = [(Y_{ba}/Z_{ba})/(Y_b/Z_b)] - 1$

Partial actual yield loss, i.e AYL_a and AYL_b represent the proportionate yield loss or gain of species 'a' and 'b' relative to their yield in pure stands (Banik, Sasmal, Ghosal, & Bagchi, 2000).

Where:

Y_{ab} is the yield of crop 'a' in the mixture

X_{ab} is sown proportion of crop 'a' in the mixture

Y_a is the yield of crop 'a' as a sole crop

X_a is sown proportion of crop 'a' as a sole crop.

Y_{ba} is the yield of crop 'b' in the mixture

Z_{ba} is sown proportion of crop 'b' in the mixture

Y_b is the yield of crop 'b' as a sole crop

Z_b is sown proportion of crop 'b' as a sole crop (Dhima et al., 2007; Neamatollahi et al., 2013).

2.6.2 Aggressivity

Aggressivity is "used to indicate how much of the relative yield increase in crop 'a' is greater than that of 'b' crop in an intercropping system" (Dhima et al., 2007). It is calculated using the following formula:

$A_a = Y_{ab}/(Y_{aa}*Z_{ab}) - Y_{ba}(Y_{bb}*Z_{ba})$ (Baldy & Stigter, 1997)

Where:

A_a is the aggressivity of crop 'a'

Y_{aa} is the yield per unit areas for sole crop 'a'

Y_{ab} is the yield of crop a when intercropped with crop 'b'

Z_{ab} is the proportion of intercropped surface area initially designated for crop 'a'

Z_{ba} is the proportion of intercropped area initially designated for crop 'b'

If A_a is = 0 both crops are equally competitive.

If A_a is negative, then crop 'a' is the dominated species

If A_a is positive, then crop 'a' is dominant (Dhima et al., 2007; Neamatollahi et al., 2013).

If the coefficient is greater than 1, then the crop has benefitted from intercropping (Baldy & Stigter, 1997).

2.6.3 Competition ratio

The competition ratio is used to measure the competition between crops in an intercrop (Dhima et al., 2007). It gives a better measure of the competitive ability of the species in the intercrop and is a superior index than relative crowding coefficient and aggressivity (Mead & Willey, 1980).

$CR_a = (LER_a/LER_b)(Zb_a/Za_b)$

Where:

CR_a is the competitive ratio of crop 'a'.

LER_a and LER_b are the land equivalent ratios of crop 'a' and crop 'b' respectively.

Zb_a and Za_b are proportions of surface area occupied at sowing by crop 'a' and crop 'b' respectively.

A competitive ratio is used to express the effects of aggression in an intercropping system.

2.6.4 Land equivalent ratio

The land equivalent ratio is a measure that illustrates the advantage or disadvantage of growing a crop in an intercropping system compared to growing it as a sole crop (Baldy & Stigter, 1997). It is defined as, "the relative land area that is required by monocrops to produce the same yield as intercrops" (Neamatollahi et al., 2013). It is calculated as follows:

$(IC_a/M_a) + (IC_b/ M_{b)} + \ldots\ldots (IC_n/ M_{n)}$

Where IC is the intercrop biomass and M is the monoculture biomass and ‘a’, ‘b’, ‘n’, are the crop species.

LER = 1 means neither species performs better or worse in an intercrop than they do in a monoculture.

LER> 1 means the intercrop uses land more efficiently.

LER< 1 means the intercrop uses land less efficiently (Baldy & Stigter, 1997).

Partial LER, which is a single fraction of the LER indicates the competitiveness of species (Baldy & Stigter, 1997).

2.6.5 Relative crowding coefficient

The relative crowding coefficient measures the relative dominance of one species over the other (Dhima et al., 2007). It is calculated using the following formula:

$K=(K_a K_b)$

$K_a= [\ (Y_{ab}\ Z_{ba})/(Y_{a}-Y_{ab})Z_{ab}]$

$K_b= [(Y_{ba}\ Z_{ab})/(Y_{b}-Y_{ba})Z_{ba}]$

Where:

Z_{ab} is the sown proportion of crop ‘a’ in the mixture.

Z_{ba} is the sown proportion of crop ‘b’ in the mixture.

Y_a is the yield of crop ‘a’ as a sole crop.

Y_b is the yield of crop ‘b’ as a sole crop.

Y_{ab} is the yield of crop ‘a’ in the mixture.

Y_{ba} is the yield of crop 'b' in the mixture.

When K is > 1 there is a yield advantage.

When K is < 1 there is a yield disadvantage.

When K = 1 there is no yield advantage (Dhima et al., 2007).

2.6.6 Monetary advantage index

MAI= [value of combined intercrops * (LER-1) / LER] (Dhima et al., 2007). The higher the monetary advantage index, the more profitable the intercropping system is relative to sole cropping (Dhima et al., 2007).

2.6.7 Intercropping advantage

Intercropping advantage indicates the economic feasibility of intercrops (Dhima et al., 2007). It is calculated using the formula below:

$IA_a = (AYL_a * P_a)$

Where:

AYL_a is the actual yield loss of crop 'a',

P_a is the commercial value of crop 'a' (Dhima et al., 2007).

2.7 Advantages of intercropping

Intercropping can be advantageous through its effects on crop yield and productivity, forage quality, resource capture and use efficiency, and pest and disease control.

2.7.1 Improving yield and land productivity

Higher yields and improved land productivity under intercropping is well documented. This increase in yield and improved land productivity is attributed to an increase in resource capture and resource conversion efficiency (Bedoussac et al., 2015; Willey, 1990).

In a two-year study in Iran, it was found that intercropping two maize varieties with legumes (vetch, bitter vetch, common bean, and berseem clover) resulted in significantly higher dry matter yield than sole cropping maize (Javanmard, Nasab, Javanshir, Moghaddam, & Janmohammadi, 2009). This was attributed to better capture and utilisation of photoactive radiation, water, and nutrients by the intercrop, compared to sole cropped maize.

Similarly, in an oat and pea intercrop study in Alaska, intercropping increased dry matter yield production (Begna et al., 2011). In this study, the highest yielding oat and pea intercrop produced 8.5% and 30% more dry matter yield compared to sole cropped oats and peas respectively. Likewise, in a study in Iran, intercropping maize with cowpeas resulted in significantly higher dry matter yield compared to their sole cropped counterparts (Eskandari & Ghanbari, 2009). Intercropped maize and cowpea produced up to 11.13 t/ha, whereas sole cropped maize and cowpeas produced 8.7 and 6.13 t/ha respectively (Eskandari & Ghanbari, 2009). The higher dry matter production under intercropping was attributed to increased light interception, higher water extraction, and the complementary consumption of nitrogen by the intercrop (Eskandari & Ghanbari, 2009).

Similarly, combining different wheat cultivars in another Iranian study resulted in up to a 25% yield increase as compared to the sole cropping of the wheat cultivars (Biabani, 2009). This was because the combination of tall and short cultivars changed the canopy structure of the crop production field, which increased the potential of radiation interception and ultimately yield (Biabani, 2009). Similar results have also been found in cereal-pea intercrop studies in Greece (Lithourgidis, Vlachostergios, Dordas, & Damalas, 2011), oat-legume intercrop studies in Australia, (Kaiser, Dear, & Morris, 2007), and maize-legume studies in Iran (Eskandari, 2012).

However, other studies have shown intercropping to either have no effect on yield or to reduce the yield altogether. In a three-year study in Alberta Canada, intercropping faba bean with either wheat or barley resulted in lower yields than the sole cropped yields of the component crops (Berkenkamp & Meeres, 1987). Likewise, in a study in Argentina, intercropping maize and soybean resulted in significantly lower seed yield of maize and soybean compared to their sole grown counterparts (Echarte et al., 2011). This was attributed to planting densities, which did not allow the two crops to thrive in an intercrop. As an example of not affecting yield, Ayub, Tanveer, Nadeem, and Shah (2004) found no significant difference in the yield of sole cropped sorghum and sorghum intercropped with rice bean in a study in Pakistan. Similarly in a two-year in a study in Uganda, intercropping Bananas with various legumes did not result in any significant difference in yield between sole cropped and intercropped bananas (McIntyre et al., 2001). Differences in the effect of intercropping on yield can be attributed to differences in the component crops of the intercropping systems and the soil and climatic conditions. All the above influence the ecological relationships in the intercropping system, ultimately affecting the yield.

Apart from yield, another way to measure the productivity of an intercropping system is by using the land equivalent ratio, LER. It is a measure that illustrates the efficiency or lack thereof of the intercropping system compared to growing the crop of interest as a sole crop (Baldy & Stigter, 1997). Studies have shown that intercropping enables higher productivity per area of land, as illustrated by various LER findings.

In a two-year study, under eastern Mediterranean conditions in Turkey, intercropping maize with either cowpea or beans resulted in better land-use efficiency (Yilmaz, Atak, & Erayman, 2008). In this study, the maize-bean and maize-cowpea intercrops had LER values of 1.61 and 1.72 respectively. This showed that 61-72% more land would be required under monocropping to produce the same amount of maize grain yield as produced under intercropping (Yilmaz et al., 2008). Similarly, in a two-year study in Iran, LER values showed higher land productivity when maize was intercropped with either cowpea or mung bean than when it was grown as a sole crop (Eskandari, 2012). In this study, LER values showed that 28-33% more land would be required for sole cropped maize to match the dry matter yields produced when maize was intercropped with either cowpea or mung bean. Furthermore, Javanmard et al. (2009) found that intercropping maize with various legumes resulted in better land productivity. LER values in this study showed that growing maize as a sole crop would require 7 to 30% more land to match intercrop dry matter yields (Javanmard et al., 2009). Similar results have also been found in pea-cereal intercropping studies in Greece (Lithourgidis, Vlachostergios, et al., 2011).

However, in a two-year bitter vetch-safflower study in Iran, it was found that intercropping the two crops at various seed ratios had no yield advantage, as shown by LER values of less than 1 in all three mixtures (Jalilian, Najafabadi, & Zardashti, 2017). This was attributed to the sowing ratios used, which did not favour the productivity of the intercrop. Differences in findings could be attributed to differences in the component crop of the intercrops and sowing ratios. These influence the ecological relationships in the intercropping system, ultimately affecting the yield, and thus the productivity of the intercropping system.

Another advantageous aspect of intercropping with regards to yield and productivity is yield stability. Intercropping has been thought to provide farmers with yield stability, especially in rain-fed agriculture systems (Umesh, Chittapur, & Jagadeesha, 2017). Yield stability under intercropping is attributed to the system's higher relative advantage in response to water, pest, and disease stress, and the security that multiple crops provide against crop failure (Willey et al., 1983). This yield stability aspect further magnifies the potential of intercropping as a sustainable crop production management tactic, especially under a changing climate.

2.7.2 Improving forage quality

Poor nutrition is one of the major limitations to livestock production (Hegarty, 2012; Yucel & Taskin, 2018). Proper nutrition requires a balanced combination of energy, protein, essential amino acids, minerals, and vitamins, and this balance varies according to production objectives, animal species, and age (Kaasschieter, De Jong, Schiere, & Zwart, 1992; Suttle, 2010; Yucel & Taskin, 2018). Intercropping can be used as a management tactic to improve animal nutrition by improving the quality of forage.

Several parameters are used to indicate the quality of forage, among which are crude protein, neutral detergent fibre (NDF), and acid detergent fibre (ADF) (Stokes & Prostko, 1998). Crude protein measures the amount of protein available in forage (Eskandari, Ghanbari, & Javanmard, 2009). The NDF measures all the fibre present in forage, whereas the ADF measures cellulose and lignin (Eskandari et al., 2009; Stokes & Prostko, 1998). High levels of NDF decrease forage intake and limit forage effectiveness in supplying energy, whereas high ADF reduces fibre digestion in livestock (Eskandari et al., 2009; Stokes & Prostko, 1998). As such forage with high levels of ADF and NDF have low palatability and digestibility in animals, and this negatively affects growth and weight gain (Eskandari et al., 2009; Rohweder, Barnes, & Jorgensen, 1978). Good quality forage, therefore, has a high crude protein content and low ADF and NDF levels.

The use of intercropping to improve the quality of forage is well documented. In a three-year study in the UK, it was found that intercropping wheat and faba beans resulted in better quality forage (Ghanbari-Bonjar & Lee, 2002). In this study, it was found that intercrops had 1.44 times more crude protein than sole cropped wheat (Ghanbari-Bonjar & Lee, 2002). Similarly, in an Alaskan study, it was found that intercropping oats with peas improved the quality of forage, by increasing the crude protein content (Begna et al., 2011). In this study, intercropped oats and peas had 15% more crude protein compared to sole cropped oats. Intercropping also lowered the ADF and NDF of forage compared to sole cropped oats, further improving the quality of the forage, as lower ADF and NDF result in better palatability and digestibility of forage by livestock (Begna et al., 2011).

Likewise, a two-year study in Iran, Javanmard et al. (2009) found that intercropping maize with various legumes not only increased the dry matter production, but also increased the ash content of forage, while simultaneously lowering ADF and NDF content (Javanmard et al., 2009). Similarly, in another Iranian study, Eskandari and Ghanbari (2009) found that intercropping maize with cowpea significantly increased the crude protein content of forage. The maize-cowpea intercrop produced up to 25% more crude protein per kg of dry matter compared to sole-cropped maize (Eskandari & Ghanbari, 2009). Similar findings have also been found in a maize-cowpea/mung bean study in Iran (Eskandari, 2012) and a 3-year oat and pea study in Finland, (Kontturi et al., 2011).

Other studies, however, have shown that legume and cereal intercrops do not always improve the quality of forage. A two-year study in Greece found that there was no significant difference in ADF and NDF content between vetch-barley and vetch -wheat intercrops and their monocultures (Dhima et al., 2007). This was attributed to the type of cultivars used in the study, the stages of maturity at harvest, and prevailing growth conditions (Dhima et al., 2007).

It is worth noting that improvement of forage quality in a cereal and legume intercrop is mostly beneficial in comparison to the cereal monocrop. In general, the legume monocrop has significantly superior forage quality. In a two-year study in Greece, the highest crude protein was found in sole cropped peas compared to when peas were intercropped with various cereals or the cereal monoculture’s (Lithourgidis, Vlachostergios, et al., 2011). Similarly, in a two-year study in Australia where cereals were intercropped with peas, it was established that when grown as a sole crop, forage peas, while producing lower dry matter yields, had higher crude protein and lower NDF concentrations (J. L. Jacobs & Ward, 2012).

Intercropping cereals with legumes is, therefore, an important management tactic in improving the quality of cereal forage crops.

2.7.3 Improving water capture and utilisation efficiency

Of the world's usable water resources, 80% are consumed by irrigated agriculture, a consumption that is not sustainable under a growing population and a changing climate (Chapagain & Riseman, 2015). Increased water use efficiency is therefore an important aspect of sustainable agriculture, especially in semi-arid regions (Chapagain & Riseman, 2015; Gaiser, De Barros, Lange, & Williams, 2004).

The water use efficiency of a cropping system can be improved either through breeding or management practices (Chapagain & Riseman, 2015). Water use efficiency is defined as “the amount of carbon assimilated as biomass or grain produced per unit area of water consumed by the crop” (Hatfield & Dold, 2019). Water use efficiency is the ratio of the above-ground biomass/grain yield to the total water used by the crop, it is influenced by canopy size and architecture, leaf morphology and anatomy, and root architecture and anatomy (Bramley, Turner, & Siddique, 2013; Rahman et al., 2017).

Efficient water utilisation under intercropping comes about as a result of spatial and temporal differences in moisture demands (Dong et al., 2018). Under intercropping water use efficiency is affected by plant density, row spacing, and the individual crop proportions (Morris & Garrity, 1993). While water consumption under intercropping can at times be higher, it can be reduced by optimising crop management practices such as irrigation, tillage and mulching practices, crop arrangement, and fertiliser regimes (Mao et al., 2012; Teng, Zhao, Chai, Hu, & Feng, 2016; Yang, Huang, Chai, & Luo, 2011; Yin et al., 2018). Total soil evaporation can also be higher under intercropping due to the longer growing season, but daily soil evaporation is lower, indicating a higher water availability (Yin et al., 2020).

Intercropping can be used to increase crop productivity and improve yield stability in water stress-prone environments (Morris & Garrity, 1993). It enhances water use efficiency in several ways. Firstly, a larger portion of evapotranspiration in intercrops is transpiration and not evaporation as compared to sole cropping (Morris & Garrity, 1993). This is because of the increased ground cover that intercropping provides (Morris & Garrity, 1993). Secondly, one crop component can have a higher water use efficiency compared to the other, increasing the overall water use efficiency of the whole cropping system in comparison to the crop with low water use efficiency (Morris & Garrity, 1993). Thirdly, the differing plant architecture in the mixture creates an environment that has a positive effect on transpiration efficiency (Morris & Garrity, 1993). The transpiration efficiency is increased due to canopy formation, which increases the crop’s resilience to moisture deficit, as the canopy reduces evaporation through shading (Gebru, 2015). The canopy also improves plant available water by improving infiltration and reducing erosion (Willey, 1990). All the above improve the transpiration efficiency. Lastly, the differences in root architecture of plants in mixtures, force plants to explore different parts of the root zone, making better use of available water resources (Willey, 1990).

The effect of intercropping in improving the water use efficiency of crop production systems is well documented. In a two-year study in Argentina, intercropping maize and soybean improved the water use efficiency by 48% compared to sole cropped soybean (Coll, Cerrudo, Rizzalli, Monzon, & Andrade, 2012). The increase in water use efficiency of the intercrop was attributed to the maize component, which inherently has a higher water use efficiency than soybean (Coll et al., 2012). Similarly, in a two-year Canadian study where wheat was intercropped with either faba bean or common bean, it was found that the intrinsic water use efficiency of wheat improved with intercropping as compared to sole cropping (Chapagain & Riseman, 2015). This was attributed to improved nitrogen nutrition in the intercrop which in turn enhanced photosynthesis and ultimately the water use efficiency of the wheat crop. Likewise in a two-year Nigerian study, in which maize and sorghum were grown, it was found that intercropped maize and sorghum had higher water use efficiency compared to their sole counterparts (Sani, Danmowa, Sani, & Jaliya, 2011). Similar results were also found in a two-year pea and maize intercrop study in China (Mao et al., 2012).

However, other studies have found intercropping ineffective in improving water use efficiency. In a two-year Chinese study, Gao et al. (2009) found that intercropping winter wheat and spring maize under strip intercropping did not improve water use efficiency despite increasing the yield. This was because even though the intercrop had a water use efficiency that was 4% greater than that of sole wheat, its water use efficiency was 23% less than that of sole cropped maize. As such the overall effect was that the intercropping system did not improve the water use efficiency (Gao et al., 2009). Similarly, in a five-year study in which switchgrass and milk vetch were investigated in China, it was found that the water use efficiency of the intercrop was significantly lower than that of the individual sole crops (Xu, Li, & Shan, 2008). The intercropped mixture had lower biomass and evapotranspiration compared to sole crops. Differences in findings in the intercropping studies can be attributed to differences in planting patterns and density, differences in the architecture of the component crops, and their overall complementarity.

2.7.4 Improving nutrient capture and utilisation efficiency

Sustainable nutrient management strategies synchronise the release of plant-available nitrogen and crop demands as a way of improving yields and reducing environmental pollution (Hauggaard-Nielsen, Ambus, & Jensen, 2003). The use of synthetic nitrogen has boosted global agriculture, increasing the amount of food that can be produced (Crews & Peoples, 2004).

However, increased use of synthetic nitrogen has come at a cost to the environment. Environmental hazards that come about as a result of the use of mineral nitrogen include soil acidification, nitrate leaching, and ammonia volatilisation (Crews & Peoples, 2004). Furthermore, the production of synthetic nitrogen requires a lot of energy leading to more negative impacts on the environment (Crews & Peoples, 2004). As such, increasing the nutrient use efficiency of cropping systems is imperative in reducing environmental degradation.

There are several ways in which intercropping increases the nutrient use efficiency of a crop production system. Firstly, increased nutrient use efficiency is attributed to plant roots extracting nutrients at different horizons in the soil (Willey, 1990). Secondly, improved nutrient use efficiency is through minimisation of nutrient loss. Under intercropping, the canopy and dense root system that forms protects the soil from erosion and desiccation by providing considerably more ground cover and holding the soil together better (Gebru, 2015; Rahnama & Latifian, 2013). Thirdly, intercropping improves nutrient use efficiency by improving nutrient availability. When a legume and non-legume are intercropped, nitrogen fixed by the legume can become available to the non-legume (Banik et al., 2000; Chapagain & Riseman, 2014; Tang et al., 2020). As such, intercropping a legume and a non-legume provides potential in low input systems to make use of nitrogen facilitation without compromising yield (Chapagain & Riseman, 2014)

Intercropping has been found to improve nutrient use efficiency in crop production systems. In a two-year study in Canada, intercropping barley with pea increased the soil mineral nitrogen compared to when barley was grown as a sole crop (Chapagain & Riseman, 2014). Soil mineral analysis showed that there was a decrease in soil nitrogen under barley monocropping. In this same study, it was also found that there was a higher number of nodules and proportion of nitrogen fixed by pea under intercropping than for sole cropped peas (Chapagain & Riseman, 2014). Under intercropping, peas developed 27-45% more nodules, and 17-19% more nitrogen was derived from biological nitrogen fixation. This was attributed to competition from the barley for nitrogen, which forced the pea to fix more nitrogen in the soil (Chapagain & Riseman, 2014). Likewise, in a greenhouse pot experiment where wheat and chickpea were under investigation, the rhizosphere of intercropped wheat and chickpea had significantly higher phosphorus concentration and there was a 65% increase in phosphorus concentration in wheat shoots under intercropping (Betencourt, Duputel, Colomb, Desclaux, & Hinsinger, 2012).

This was attributed to the ability of legumes to increase the availability of inorganic phosphorus through acidification of the rhizosphere as a result of biological nitrogen fixation (Betencourt et al., 2012).

Similarly, in a study in Denmark, intercropping barley with either pea or faba bean increased the proportion of plant nitrogen derived from biological nitrogen fixation (Knudsen, Hauggaard-Nielsen, Jørnsgaard, & Jensen, 2004). This was attributed to interspecific competition for mineral nitrogen which forced the legume in the mixture to biologically fix more nitrogen. Similar results were also found in a two-year lysimeter experiment in Denmark, where interspecific competition in a barley-pea intercrop caused an increase in pea biological nitrogen fixation (Hauggaard-Nielsen et al., 2003). Furthermore, in a study in France that encompassed 16 experimental sites, it was found that pea-wheat intercrops had a higher nutrient use efficiency, as evidenced by intercrop fields requiring less than half the amount of nitrogen per ton of grain produced compared to sole cropped wheat (Pelzer et al., 2012).

However, in a study in Tanzania cowpea was found to fix twice as much nitrogen when grown as a sole crop than when intercropped with maize, indicating that intercropping did not have an advantage on nutrient availability and ultimately the nutrient use efficiency (Vesterager, Nielsen, & Høgh-Jensen, 2008). Similarly, a Canadian study found that while intercropping barley with peas increased the biological nitrogen fixation of peas compared to sole cropping, the amount of nitrogen transferred from the pea to the barley was negligible (Izaurralde, McGill, & Juma, 1992). Differences in findings can be attributed to the differences in the complementarity of the crops, soil characteristics, and climatic conditions.

2.7.5 Improving radiation capture and utilisation efficiency

Solar radiation is an integral component of crop growth as it is the source of energy for photosynthesis, thus determining levels of crop productivity (Keating & Carberry, 1993). Plants intercept radiation using leaves and other green organs and use this light to carry out photosynthesis to produce biomass (M Tsubo, Walker, & Mukhala, 2001).

Under conditions where water and nutrients are not limiting, yield output is dependent on the capture and utilisation of photoactive radiation (Awal, Koshi, & Ikeda, 2006; Keating & Carberry, 1993; Yahuza, 2011). While solar radiation is a more reliably available growth resource than water and nutrients, it cannot be stored and must be used immediately (Keating & Carberry, 1993; Yahuza, 2011).

A crop canopy is defined "in terms of photosynthetically active or green leaf area" while the leaf area index is defined as "the amount of green leaf area per unit of ground area" (Keating & Carberry, 1993). The radiation use efficiency on the other hand is, "the amount of dry matter produced per unit of intercepted solar radiation" (Keating & Carberry, 1993). The amount of light intercepted by a crop is a factor of the crop cycle duration, the rate of leaf area development from emergence, and the highest leaf area index (Keating & Carberry, 1993; Yahuza, 2011). The efficient use of photoactive radiation is a crucial determinant of yield in crop production (Awal et al., 2006).

Intercropping has the potential to produce a wide range of canopies due to the different combinations of crops that vary in space and time, leaf characteristics, and plant height (Keating & Carberry, 1993; Morris & Garrity, 1993). Intercrops outperform sole crops either by increasing the total amount of light intercepted, increasing the radiation use efficiency, or a combination of both (Awal et al., 2006; Keating & Carberry, 1993; Willey, 1990; Yahuza, 2011; Zhang et al., 2008). An increase in the amount of radiation captured can be a result of either temporal or spatial complementarity (Keating & Carberry, 1993; Yahuza, 2011).

Most intercropping mixtures are composed of dominant and subordinate crop species (Awal et al., 2006). In most cases, the dominant species is a cereal, due to its tall stature and isobilateral leaves, while the subordinate species is usually a legume (Awal et al., 2006). The two species form canopy geometrics that can either be two separate canopies or intermingling of the two. In cases where two canopies are formed, the dominant species grows unaffected by the subordinate, whereas the growth of the subordinate is influenced by the dominant species, particularly because of shading (Awal et al., 2006). An example of spatial complementarity would be a tall crop that does not make complete use of seasonal photoactive radiation planted at optimum density and intercropped with a shorter plant. In such a scenario, planting a shorter plant will not affect the radiation intercepted by the taller plant, but will increase the total amount of radiation intercepted, thereby increasing the output per unit area (Keating & Carberry, 1993; Yahuza, 2011).

Increasing light interception can also be achieved by combining a fast and slower growing crop, resulting in temporal complementarity (Keating & Carberry, 1993). Short-duration crops make good use of short growing seasons, but waste radiation in a long season. Long-duration crops make use of longer growing seasons but waste resources in the early days of the growing season due to poor canopy formation (Keating & Carberry, 1993).

A combination of the two can therefore make better use of a growing season through improved temporal patterns of canopy development (Keating & Carberry, 1993).

The ability of intercropping to increase radiation capture and use efficiency is well documented. In a three-year study in China, it was found that maize strips intercropped with soybean intercepted 77% more photoactive radiation than maize monoculture (Liu et al., 2018). The intercrop also had a higher radiation use efficiency which resulted in high LER, illustrating the intercropping advantage (Liu et al., 2018). Similarly, in a one-year study in the southeast pampas of Argentina, intercropped maize and soybean intercepted the highest amount of photoactive radiation and improved the radiation use efficiency, compared to sole cropped soybean (Coll et al., 2012). An increase in radiation productivity for this intercrop compared to the sole cropped soybean was due to an increase in radiation capture of 13% and an increase in the radiation use efficiency of 63%.

Similarly, in a one-year maize-peanut study in Japan, intercropped peanuts were found to have a radiation use efficiency that was 79% higher than sole cropped peanuts as a result of the canopy dynamic that was formed (Awal et al., 2006). Likewise, in a three-year wheat and cotton intercropping study in China, it was found that while monoculture wheat and cotton intercepted significantly more light than their respective intercropped counterparts, the total radiation captured by the two crops was significantly higher than either sole crop (Zhang et al., 2008). Increased productivity, as illustrated by land equivalent ratios in this study, was attributed to an increase in total radiation captured only, as there was no significant difference in the radiation use efficiency (Zhang et al., 2008).

Similarly in a spring wheat-maize intercrop study in China, it was found that while radiation interception rates were higher in sole cropped wheat and maize, the total intercepted radiation in the intercrop was higher (Wang et al., 2015). This resulted in higher grain yields in the intercrop, an increase in productivity that was attributed to an increase in radiation capture, and not radiation use efficiency (Wang et al., 2015).

Likewise, Chimonyo, Modi, and Mabhaudhi (2018) found that intercropping sorghum with either cowpea or bottle gourd increased the radiation capture by 38% and radiation use efficiency by 93%, as compared to sole cropped sorghum. Likewise, a study in the Netherlands showed that intercropping wheat and maize resulted in a higher radiation interception than their respective sole crops (Gou et al., 2017).

This was attributed to the extension of the growing season since intercropping allowed the two crops to use radiation during different parts of the growing season (Gou et al., 2017). Similar results have also been found in maize-bean intercrop studies in South Africa (Mitsuru Tsubo, Mukhala, Ogindo, & Walker, 2003).

Other studies however have found intercropping to have a negative effect on radiation capture and use. In a two year study in India, where intercropping of upland rice and legumes was investigated, it was found that though intercropping rice with pigeon pea increased intercepted radiation by up to 16%, the radiation use efficiency in this intercrop was reduced by up to 42% compared to sole cropped pigeon pea (Ramakrishna & Ong, 1994). This increase in light interception was attributed to fast canopy formation by the pigeon pea as compared to rice which has a slow canopy formation, but it was not enough to make up for the reduction in radiation use efficiency. Similarly, Coll et al. (2012) found that there was no improvement in radiation use efficiency under sunflower-soybean intercropping compared to their respective sole crops, despite intercropping extending the growing period of the two crops. This was attributed to the two crops having similar radiation capture and use efficiency.

Differences in findings in the effect of intercropping on radiation utilisation can be attributed to the differences in photosynthetic efficiencies of the crops, canopy architecture, and their overall complementarity.

2.7.6 Pest and disease control

Pests and diseases have the potential to cause crop yield losses that range from 18 to 50% depending on the crop and pest/disease (Oerke, 2006). Crop protection is therefore an integral part of crop production and meeting global food demand (Oerke, 2006). Despite the many benefits of chemical control, long-term and excessive use can lead to contamination of food, water, and the environment (Gomes, Silva, Silva, Rodrigues Filho, & Santos, 2007). Intercropping has the potential to provide environmentally friendly farming systems due to its multifunctional capabilities in soil protection and non-chemical pest and disease suppression (Cook, Khan, & Pickett, 2007; Fininsa, 1996; Ramert et al., 2002).

The reduction of pests under intercropping occurs in the following ways:

a) The dispersal of plants as a result of intercropping makes it harder for pests to find individual plants (Degri & Samaila, 2014; Smith & McSorley, 2000).
b) Crops may serve as trap crops diverting pests from the main crop (Cook et al., 2007; Pickett, Woodcock, Midega, & Khan, 2014; Smith & McSorley, 2000).

c) Plants may have repellent properties towards pests (Cook et al., 2007; Pickett et al., 2014; Smith & McSorley, 2000).
d) The diverse ecological system under intercropping enables natural enemies to thrive and so be found in abundance (Mousavi & Eskandari, 2011; Ramert et al., 2002).

Various studies have documented the effectiveness of intercropping as a pest control tactic. In a Nigerian study, intercropping maize with landrace legumes was found to reduce pest incidence (Ibeawuchi et al., 2007a). Intercropped maize had a stalk borer (*Papaipema nebris*) incidence that ranged from 1.3-2.7% whereas the incidence of the pest under sole cropped maize was up to 16.9% (Ibeawuchi et al., 2007a). This was attributed to the heavy and diverse morphology resulting from intercropping, which in turn reduced pest pressure in the system. Similarly in another two-year study in Nigeria, it was found that intercropping reduced the effect of tomato fruit borer (*Helicoverpa armigera)* when tomato was intercropped with maize (Degri & Samaila, 2014). In this study, the sole cropped tomato had almost twice as many damaged fruits as the intercropped tomato. This was attributed to lower pest build-up under intercropping, and maize acting like a barrier against the pest. Subsequently, the highest fruit weight and fruit yield were under intercropping (Degri & Samaila, 2014).

Likewise in a one-year study in Zimbabwe, intercropping banana with cowpea and sunn hemp significantly reduced the effect of burrowing nematode (*Radopholus similis*) (Chitamba, Manjeru, Chinheya, & Handiseni, 2014). This was attributed to the two crops being poor hosts of the pest. Intercropping of bananas with sunn hemp also significantly reduced the number of nematodes and this was attributed to sunn hemp's ability to produce exudates which negatively affected the nematodes (Chitamba et al., 2014). Similarly, in a two-year study in Uganda where the effect of intercropping on termites and predatory ants in maize was investigated, intercropping maize with soybean significantly reduced the proportion of damaged plants compared to sole cropped maize (Sekamatte, Ogenga-Latigo, & Russell-Smith, 2003). In this study, when fields were left unprotected from termites, intercropping produced significantly higher yields. Similar results have also been found in studies on pod-sucking bugs in soybean intercrops in Nigeria (Sastawa, Lawan, & Maina, 2004), *Chrysomelidae* beetle pests studies in Costa Rica (Risch, 1980), and root tuber-landrace intercrop studies in Nigeria (Ibeawuchi et al., 2007b).

However, in other studies, intercropping has not been successful as a pest control management tactic and has even had the opposite effect. In a study on maize in Uganda, intercropping was found to increase the number of predatory ants when maize was intercropped with legumes. This was attributed to intercropping providing a conducive environment for the ants to thrive (Sekamatte et al., 2003). Similarly in a three-year study in Uganda, intercropping of bananas with various legumes did not result in any significant difference in terms of weevil damage and the number of weevils in traps (McIntyre et al., 2001). This was attributed to the biology of the banana weevil which travels relatively low distances and is sedentary for extended periods, which made the intercropping intervention unsuccessful in disrupting its life cycle. In this same study, intercropping banana with *Tephrosia vogeli* did not significantly control the nematode *Radopholus similis,* but rather resulted in a 49% increase in the pest (McIntyre et al., 2001). This increase in nematodes was attributed to *Tephrosia vogeli* providing a conducive environment for the pest.

Differences in findings among studies can be attributed to differences in the pest of interest and its biology and the component crops of the intercrops. Understanding the biology of both the pest and the component crops is therefore crucial in using intercropping as a pest management tactic, as it enables the farmer to determine whether intercropping will reduce pest incidence or exacerbate the problem.

Intercropping affects disease incidence in the field by affecting both the dispersal and non-dispersal aspects of the disease cycle (Boudreau, 2013). Intercropping reduces disease in the following ways:

a) It reduces the incidence of disease by disrupting spore dispersal. This is due to a reduction in wind speed and thus the distance spores can be transported. Intercropping also results in spores landing on non-host plants (Boudreau & Mundt, 1992; Gómez-Rodrıguez, Zavaleta-Mejıa, Gonzalez-Hernandez, Livera-Munoz, & Cárdenas-Soriano, 2003).
b) It reduces disease through changes in the microclimate, by affecting the temperature and humidity due to changes in the canopy (Fininsa, 1996; Gómez-Rodrıguez et al., 2003).
c) It reduces disease through the allelopathic effects of non-host plants on the pathogen (Gómez-Rodrıguez et al., 2003).

The use of intercropping to control diseases is well documented. In a two-year study in Ethiopia, mixed cropping of beans and maize reduced the severity of common bacterial blight and rust by up to 23% and 51% respectively compared to when beans were grown as a sole crop (Fininsa, 1996). Disease reduction under intercropping was attributed to change in the microclimate, as intercropping reduced temperatures due to canopy structure changes. This reduction in temperature reduced the severity of common bacterial blight, as high temperatures favour the development of the disease (Fininsa, 1996). Furthermore, the tall canopy formed by maize not only served as a barrier against the spreading of spores but also reduced wind velocity, reducing the spread of lesions from spores and ultimately reducing rust (Fininsa, 1996). Similarly in a study in Mexico, intercropping tomato with marigold reduced early blight disease, a common leaf disease of tomato. In this study, it was found that intercropped tomatoes had 41% lower leaf damage at 16 weeks after planting (Gómez-Rodrıguez et al., 2003). Furthermore, conidia formation and number of germinated tubes per conidium registered on inoculated tomato leaflets was much lower in intercropped tomato than in sole cropped tomato. The reduction of early blight disease in intercropped tomato was attributed to the allelopathic effect of marigold on *Alternaria solani,* the significant reduction in the microclimate relative humidity, and marigold forming a barrier that reduced the dissemination of conidia (Gómez-Rodrıguez et al., 2003).

Likewise, in a two-year study in Ethiopia, intercropping beans with maize and sorghum resulted in lower incidence and slower progression of common bacterial blight (Fininsa & Yuen, 2002). Common bacterial blight disease incidence and severity were 32% and 21% lower under intercropping as compared to when beans were grown under monoculture (Fininsa & Yuen, 2002). In this study, reduction in the disease was attributed to change in microclimate, as well as a reduction in host density and induced resistance (Fininsa & Yuen, 2002). Likewise, an evaluation of pests and diseases in bean and maize systems from six research stations in Kenya, with very few exceptions, showed disease incidence was lower under intercropping than when beans were grown as a sole crop. This was attributed to changes in the microclimate and barrier formation by the maize, both of which reduced the development of the diseases (Van Rheenen, Hasselbach, & Muigai, 1981).

However, intercropping does not always favour the reduction of diseases. In the above-mentioned study across six research stations in Kenya, it was found that the severity of white mould disease, a significant disease of common bean, increased when beans were intercropped with maize than when grown in a pure stand (Van Rheenen et al., 1981).

Intercropping, therefore, has the potential to be used as an alternative to chemical disease control but just like with pest control, knowledge of the biology of the pathogen and component crops is essential for success.

2.7.7 Weed control

Weeds are a limiting factor for crop production and have the potential to cause yield losses of up to 34% when left unmanaged (Oerke, 2006). Yield loss due to weeds depends on the competition period, the crop, the number of weeds per area, and the crop development stage (Mobasser, Vazirimehr, & Rigi, 2014). Aside from yield loss, weeds have been found to reduce grain quality, host pests, and diseases, and cause harvesting problems (Mobasser et al., 2014). The limiting effects of weeds are further magnified in resource-poor smaller holder farmer production systems (Ibeawuchi et al., 2007a). The use of agrochemicals, while beneficial, has resulted in soil and water pollution and pest and weed resistance (Gomes et al., 2007). Intercropping is an alternative management tactic for weed control that can be used on its own, or as a part of an integrated weed management program.

Intercropping reduces weeds in two ways. Firstly, the growing of more than one crop results in the more efficient use of growth resources, leaving very little for weeds to thrive off of (Barsila, 2018; Gebru, 2015; Gomes et al., 2007; Mobasser et al., 2014). Secondly, weeds in an intercropping system can be reduced by the allelopathic effect of compounds produced by one of the component crops (Barsila, 2018; Gebru, 2015; Gomes et al., 2007; Mobasser et al., 2014).

In a two-year study in Nigeria, intercropping was found to suppress weeds and significantly reduce weed weight (Ibeawuchi et al., 2007a). Intercropping yam with mucuna resulted in a weed weight of 0.83 t/ha, whereas under sole cropped yam, the weed weight was as high as 1.09 t/ha. Low weed weights were attributed to the shading effects of the mucuna on weeds when it was staked, and its creeping effect that formed a thick canopy on the ground when it was not (Ibeawuchi et al., 2007a). Similarly in a study in India, intercropping pearl millet with either cluster bean or moth bean significantly reduced the total number of weeds and weed dry matter compared to when millet was grown as a sole crop (Kiroriwal & Yadav, 2013**).** The reduction of weeds in this study was attributed to a higher crop canopy under intercropping than under sole cropping. Likewise in a 2-year study in Nigeria, it was found that intercropping maize with egusi melon significantly reduced the weed density and dry weight of weeds compared to sole cropped maize (Omovbude, Udensi, & Orluchkwu, 2017).

In this study, intercropping reduced the weed density by 48.8% and 50.91% at 6 and 12 weeks after planting respectively. The reduction of weeds was attributed to the ground canopy cover formed by the egusi melon and the aggressiveness of its vines. However, at three weeks after planting, there was no significant difference between sole crops and the intercrop as the canopy in the intercrop had not yet progressed sufficiently to confer weed control (Omovbude et al., 2017). Similarly in a three-year study in Canada, intercropping of spring wheat with canola resulted in significantly lower weed biomass than when wheat was grown as a sole crop (Szumigalski & Van Acker, 2005). Likewise, in a three-year study in Spain, it was found that intercropping faba bean and peas with oats significantly controlled infection by *Orobanche crenata*. The number of *O. Crenata* plants per host decreased with an increase in oat density, this was attributed to the allelopathic effect of cereal roots on the weedy root parasite (Fenández-Aparicio, Sillero, & Rubiales, 2007). Similarly, in a two-year study in Nigeria, intercropping maize with cassava reduced the weed biomass by 37% compared to when maize was grown as a sole crop (Olasantan, Lucas, & Ezumah, 1994).

However, in a maize- cowpea study in Brazil, it was found that intercropping did not have a significant effect on weeds, as no significant difference was found in weed biomass between an unweeded maize plot and the intercrop plot. This was attributed to cowpea's poor weed control abilities in this intercrop combination (Gomes et al., 2007). Similarly in an organic study in Sweden, it was found that lower mean weed biomass was found when faba bean was grown as a sole crop than when it was intercropped with maize (Stoltz & Nadeau, 2014). In this study, while intercropping decreased the weed biomass for maize, it did not decrease the weed biomass for faba bean, as the sole cropped faba bean had 14% less weed biomass (Stoltz & Nadeau, 2014).

The differences in findings in these studies illustrate the importance of the crop type as a factor in determining weed control in intercropping. The success of weed control under intercropping is largely based on the complementarity of the two crops to ensure more efficient utilisation of growth factors. As such, crop growth habits and timing of physiological stages are very important in choosing the crops to be combined for intercropping to control weeds.

2.8 Disadvantages of intercropping

While intercropping is a beneficial crop production tactic, it has some disadvantages.

2.8.1 Reduction in yield

The reduction of yield under intercropping is well documented. This reduction in yield occurs due to aggressive competition that occurs between crops in an intercrop resulting in poor water, light, and nutrient use efficiencies (Capstaff & Miller, 2018; Lithourgidis, Dhima, Vasilakoglou, Dordas, & Yiakoulaki, 2007). Furthermore, in cases of combined harvesting, the differences in growth rates and optimal harvests periods often result in one of the two crops being harvested either too early or too late (Capstaff & Miller, 2018).

In a two-year study in Greece, where barley and wheat were intercropped with common vetch, it was found that growing barley and wheat as sole crops resulted in higher dry matter production as compared to intercropping the two cereals with vetch (Lithourgidis et al., 2007). In this study intercropping resulted in a 23.4% yield reduction. This was attributed to aggressive competition for resources in the intercrop which reduced the growth rate and ultimately the yield (Lithourgidis et al., 2007). Similarly, in a study in India, intercropping pea, gram, and lentil with mustard resulted in an economic yield decrease of 46%, 56%, and 41% respectively compared to their monocultures (Banik et al., 2000). The higher yield under sole cropping was attributed to the limited competition and disturbance in the sole cropped environment. Likewise, a maize-haricot bean study in Ethiopia found that intercropping significantly reduced the grain yield compared to their sole cropped counterparts. This was attributed to aggressive competition and less complementarity between the two crops (Adafre, 2016). Thus, when crops are not carefully chosen, intercropping can have a negative effect on crop production.

2.8.2 Increase in labour demand

The mixing of different species under intercropping increases labour and oversight requirements, which makes intercropping challenging and resource-consuming (Boudreau, 2013; Capstaff & Miller, 2018).The practicality of managing agronomic practices such as spraying agrochemicals, sowing, and harvesting becomes challenging due to the differences in the component crops being grown (Umesh et al., 2017).

Intercropping can therefore be labour- intensive, particularly for developing countries where the majority of farmers still use simple tools for cultivation (Lithourgidis, Dordas, et al., 2011).

Its labour-intensive nature can make it time-consuming and a non-economically viable system (Ramert et al., 2002; Shaw et al., 2009). For example, a maize-cowpea study in Mozambique showed that intercropping required 36% more weeding labour, as compared to sole cropping (Rusinamhodzi, Corbeels, Nyamangara, & Giller, 2012). This increase was not due to an increase in weed intensity, but rather due to the need for more careful and frequent weeding (Rusinamhodzi et al., 2012). Intercropping can therefore be challenging where labour is limited, or where an increase in labour offsets the economic advantages of the system.

2.8.3 Pest and disease build-up

Intercropping can encourage pest and disease build-up. This occurs when the component crops are susceptible to the same pests and diseases (Capstaff & Miller, 2018; Mousavi & Eskandari, 2011). Furthermore, the shading that occurs under intercropping can create a micro-environment that increases pests and diseases in the field (Mousavi & Eskandari, 2011).

A study across 50 research stations in Kenya established that white mould disease, a significant disease of common bean was more severe when beans were intercropped with maize than when grown in a pure stand (Van Rheenen et al., 1981). Likewise (Sekamatte et al., 2003) in a maize study in Uganda found that intercropping the cereal with legumes increased the number of predatory ants in the field. This was attributed to intercropping providing a conducive environment for the ants to thrive (Sekamatte et al., 2003). Furthermore in another study in Uganda, intercropping Banana with *Tephrosia vogeli* increased the incidence of root nematodes by 49%, which was attributed to the grass providing a conducive environment for the nematodes (McIntyre et al., 2001). Crop and pathogen knowledge, therefore, becomes very important in using intercropping as a pest and disease control strategy.

2.8.4 Poor mechanisation potential

Mechanisation, which is characteristic of industrialised crop production, is either inefficient or impossible under intercropping. This is because most machines for sowing or harvesting are made for fields that are uniform in nature (Boudreau, 2013; Lithourgidis et al., 2011). Differences in planting patterns, the timing of agronomic activities, and crop physiology call for either alterations to machines or production of specific machines for mechanisation to work under intercropping, which can be expensive (Biabani, 2009; Capstaff & Miller, 2018).

This limits the application of intercropping for industrial and large-scale production levels since machine modifications to suit intercropping can be more expensive than they are worth (Echarte et al., 2011; Geno & Geno, 2001; Willey et al., 1983).

2.9 Importance of cereal and legume forage intercropping systems

Cereal-legume intercrops are the most common and successful annual forage intercrops around the world due to their ability to meet the nutritional needs of animals (Dhima et al., 2014; Eskandari et al., 2009). The growing of cereals and legumes as sole crops is not considered ideal for hay and forage production, as the total exclusion or low inclusion of either species produces forage of inferior quality (Ayub, Tanveer, Nadeem, Tahir, & Ibrahim, 2008; Osman & Nersoyan, 1986). When grown as sole crops, legumes and cereals do not provide a good balance of forage yield and quality (Carpici & Celik, 2014). Cereals are high yielding with high carbohydrate content, but have a low protein content, making them poor quality forage (Kocer & Albayrak, 2012; Nadeem, Ansar, Anwar, Hussain, & Khan, 2010; Osman & Nersoyan, 1986). Legumes on the other hand have a high protein content but are low yielding and susceptible to lodging (Kocer & Albayrak, 2012; Nadeem et al., 2010; Osman & Nersoyan, 1986). As such, despite being a high-quality forage, they have low production potential. The growing of cereal and legumes in mixtures is therefore a way to improve yield and quality of fodder, and increase fodder palatability and digestibility (Ibrahim, Ayub, Tanveer, & Yaseen, 2012; Osman & Nersoyan, 1986).

2.10 Factors affecting the yield and quality of cereal and legume forage intercropping systems

The yield and quality of cereal and legume forage intercrops is a factor of the component crop species in the intercrop and their respective sowing ratios.

2.10.1 Crop species

Due to the intrinsic differences that are found in crop species, the choice of cereal and legume combination determines the yield and overall quality of forage produced from intercropping. Different crop species, based on their growth habits and canopy structure, influence the relationship dynamics, i.e., competition and complementarity, ultimately affecting the resulting yield (Biabani, 2009; Eskandari & Ghanbari, 2009; Ibrahim et al., 2014; Javanmard et al., 2009). With regards to yield quality, differences in carbohydrate and protein content arise among different crops in the cereal and legume categories, thus different crop combinations result in forage of varying quality (Ibrahim et al., 2012; Osman & Nersoyan, 1986).

In a 2- year study in Pakistan, in which Maize was grown in combination with different legumes, i.e. sesbania, cluster bean, and cowpea; the yield of mixtures was significantly affected by the type of legume (Ibrahim et al., 2014).

In this study, the highest dry matter yield was in the maize-sesbania mixture, which had a yield that was 30% and 32% higher than that of the maize-cowpea and maize-cluster bean mixtures respectively. The high dry matter yield in the maize-sesbania mixture was attributed to the tall growth habit of sesbania that allowed it to thrive in the intercrop, resulting in a higher yield compared to cowpea and cluster bean, which are short growing legumes and whose growth was negatively affected by the tall maize crop in the mixture (Ibrahim et al., 2014).

Similarly, in another study in Pakistan, intercropping of vetch with different cereals resulted in significantly different yields. In this study, the highest yield of 9.28 t/ha was found in the oat-vetch mixture, followed by a yield of 5.69 t/ha in the vetch-barley intercrop, and lastly a yield of 5.22 t/ha in the vetch-wheat intercrop (Nadeem et al., 2010). Furthermore, in a USA study, the intercropping of pea with different cereals resulted in mixtures with varying forage yield and quality. The pea-oat intercrop produced a significantly higher yield than the pea-barley intercrop (Carr, Horsley, & Poland, 2004). This was attributed to the pea-oat intercrop being better adapted to the low nitrogen conditions the trial was grown in than the pea-barley intercrop. However, for yield quality, the pea-barley intercrop was found to be superior as it had a higher crude protein content and lower ADF and NDF content. The pea-barley intercrop had 25.9% more crude protein, 5.7% and 7.9% lower ADF and NDF content respectively, compared to the pea-oat intercrop (Carr et al., 2004).

Likewise, in a 2-year study in Turkey, intercropping barley with different legumes significantly affected the yield and quality of the resulting intercrop. In this study, at a sowing ratio of 75% barley: 25% legume, the barley-vetch intercrop had a significantly higher green forage yield of 10.71t/ha, compared to the barley-grass pea intercrop with 9.29 t/ha (Karadag & Buyukburc, 2003). The barley-grass pea intercrop however had a significantly higher crude protein content of 18.9% compared to the vetch-barley intercrop with 16.86%, at the 25% barley: 75% legume seed proportion. In another two-year study in Pakistan, it was found that the legume type influenced the quality of the forage. In this study, in which maize was intercropped with either cluster bean, cowpea, or sesbania it was found that the highest crude protein at all seed ratios was found in sesbania, whereas the highest total ash was found in sole cropped cowpea (Ibrahim et al., 2012). The differences in crude protein and total ash content among the three legumes were attributed to differences in the genetic constitution of the legumes (Ibrahim et al., 2012).

Likewise in a study in Greece, the intercropping of faba bean with different cereals resulted in different dry matter production levels (Dordas & Lithourgidis, 2011). In this study, a faba bean-triticale intercrop produced up to 39% more dry matter yield than a faba bean-oat intercrop.

Different crop combinations result in forages of varying yield and quality. Thus, determining the right crop combination is important in meeting forage production objectives.

2.10.2 Sowing ratios

The sowing ratios of crops in mixtures is an important factor in determining the yield and quality of fodder, and the overall efficiency of an intercropping system (Osman & Nersoyan, 1986; Uzun & Ferda, 2012; Willey & Osiru, 1972). This is because the sowing ratio determines the plant population, which determines the relative abilities of species in a mixture and subsequently the levels of competition and complementarity (Lithourgidis & Dordas, 2010; Willey & Osiru, 1972). The sowing ratio also determines whether the main competition in the mixture will be interspecific or intraspecific (Willey & Osiru, 1972). In cases where there is higher intraspecific competition, the two-component crops explore different niches of the environment, as opposed to competing for the same growth factors (Eskandari et al., 2009; Willey & Osiru, 1972).

In general, the more dominant species in a mixture utilises a greater proportion of the environmental resources compared to the subordinate species (Willey & Osiru, 1972). As such if the dominant species has a higher yield potential, increasing its proportion will increase yield, giving the mixture a yield advantage over the monoculture crop at similar sowing proportions (Willey & Osiru, 1972). Yield advantage in mixtures occurs when the increased yield per plant of one species more than compensates for the decrease in the other species (Willey & Osiru, 1972). In general, legumes tend to be less competitive than cereals and may need to be planted at higher seed ratios than cereals for mixtures to achieve intercropping benefits (Lithourgidis & Dordas, 2010).

Regarding yield quality, the seeding ratio determines the percentage of either cereal or legume in the harvested forage, which in turn affects the crude protein, ADF, and NDF content, thus determining the overall quality of the forage (Carpici & Celik, 2014; Dhima et al., 2014; Erol, Kaplan, & Kizilsimsek, 2009). As such, determining the correct balance of cereal and legume proportion in an intercropping mixture is an important factor in the improvement of forage yield and quality (Ayub et al., 2004; Ayub et al., 2008).

2.10.2.1 Effect of sowing ratios on yield and productivity

Studies around the globe have shown that the proportion of cereals and legumes in mixtures affect the yield and productivity of the mixture. In general, increasing the proportion of cereal in the mixture increases the dry matter yield of mixtures, as cereals have a high dry matter production potential compared to legumes.

In a two-year study in Pakistan, the rate at which sorghum was intercropped with rice bean was found to have a significant effect on dry matter yield (Ayub et al., 2004). In this study, the highest dry matter yield of 13.28 t/ha was found in the sole cropped sorghum, while the lowest yield of 6.89 t/ha was found in the sole cropped rice bean (Ayub et al., 2004). Among the mixtures, the highest dry matter yield was found in 75% sorghum: 25% rice bean mixture, with a yield of 11.97 t/ha, though its yield was not significantly different from the yield of the other seed proportions (i.e., 50:50, 65:35, 25:75 sorghum-rice bean ratios). The lowest dry matter yield of 10.49 t/ha was found in the 25% sorghum: 75% rice bean treatment, this was attributed to the low cereal proportion in the mixture, i.e. the high proportion of the legume did not significantly contribute to the overall yield since rice bean has a low dry matter production potential (Ayub et al., 2004).

Likewise, in a two-year study in Greece, in which oats grown in combination with two faba bean varieties were evaluated, the proportion of the legume and cereal in the mixture was found to significantly affect the dry matter yield (Dhima et al., 2014). The highest dry matter yield was found in sole cropped oats, 2.3 times greater than that of mixtures, while the lowest dry matter yield was in the sole cropped Polykarpe faba bean variety. The highest dry matter yield among the mixtures was in the 75% oat: 25% faba bean mixture, it was higher than the dry matter yield of both sole cropped faba bean cultivars, but not significantly different from the yield of the other mixtures (Dhima et al., 2014). In this study, yield increased with an increase of cereal in the mixture. The total land equivalent ratios in this study were not significantly affected by the seeding ratios, and all the mixtures had LER values of less than 1, showing that there was no intercropping advantage (Dhima et al., 2014).

Likewise in a two-year study in Turkey in which oat and common vetch were grown at varying sowing ratios, the sowing ratios significantly affected the yield (Erol et al., 2009). The highest dry matter yield of 6.32 t/hectare was found in the 45% oats: 55% common vetch mixture and this was significantly higher than all the other mixtures and sole cropped vetch. In this study, the yield of the mixtures decreased when the vetch proportion increased above 55% (Erol et al., 2009). Similarly, in a two-year study in Pakistan where maize was grown in combination with legumes under irrigated conditions, the dry matter yield was significantly affected by the ratio of cereals to legumes in the intercrop (Ibrahim et al., 2014). The highest dry matter yield in mixtures was when maize was intercropped with a legume at a ratio of either 25% legume: 75% maize or 50% legume: 50% maize, with the highest yield being in the 50% sesbania: 50% maize mixture (Ibrahim et al., 2014). All mixtures in this study gave an LER of greater than 1, indicating a clear yield advantage of growing the crops in mixtures, but there were no significant differences between sowing ratios.

Similarly, in a two-year common vetch-annual ryegrass intercropping study in Turkey, the seed ratios of the legume and cereals significantly affected the yield. Among the mixtures, the highest yield of 13.95 t/ha was produced by the 25% vetch: 75% annual ryegrass mixture while the lowest yield of 12.75 t/ha was produced by the 75% vetch: 25% annual ryegrass mixture (Carpici & Celik, 2014). Likewise, a one-year corn-soybean Malaysian study showed that the seed ratio of the two crops significantly affected the dry matter yield. In this study, the 75% corn: 25% soybean mixture produced a significantly higher yield compared to the 25% corn: 75% soybean mixture (Baghdadi et al., 2016). In this study, yield increased with an increase in cereal in the mixture. Similarly, in a two-year pea and oat intercrop study in Turkey, the dry matter yield of mixtures was found to increase with an increase in cereal in the mixture. In this study, the highest dry matter yield of 13.58 t/ha was found in the 25% pea: 75% oat, whereas the lowest yield of 10.15 tonnes was found in the 75% pea: 25% oat mixture (Uzun & Ferda, 2012).

However, other studies have shown that an increase in the cereal component in the mixture does not always increase the yield. In a vetch-cereal and pea-cereal study in Syria, it was found that forage production increased with an increase in the proportion of legume in the mixture (Osman & Nersoyan, 1986). In this study, the 66% legume: 33% cereal mixtures out yielded all the other mixtures and the monocrop cereals. This was attributed to complementarity in the mixture as a result of the crops utilising different layers of the soil profile (Osman & Nersoyan, 1986). Increasing the proportion of legumes increased the legume component yield without reducing the total dry matter. Likewise, a pea-barley study in the UK found that yield increased with an increase in pea in the mixture (Ayub et al., 2008). This was attributed to the ability of the component crops to utilise different soil layers without competing against one another.

In this study, the 50% barley: 50% pea treatment outyielded the 75% barley: 25% pea and the 100% barley treatments. Differences in findings can be attributed to differences in the complementarity of the crops used in the studies.

2.10.2.2 Effect of sowing ratios on forage quality

The ratio at which cereal and legumes are sown in an intercrop affects the quality of forage since the biological makeup of cereals and legumes is different, resulting in differences in carbohydrate, crude protein, and fibre content (Eskandari et al., 2009; Kocer & Albayrak, 2012; Nadeem et al., 2010; Stokes & Prostko, 1998). Studies have shown that increasing the proportion of legumes in the intercrop increases the overall quality of the forage. This is because legumes tend to be higher in crude protein and low in ADF and NDF, making them more palatable, nutritious, and digestible than cereals.

In a two-year, common vetch-triticale/ryegrass study in Turkey, seeding ratios were found to significantly affect forage quality (Carpici & Celik, 2014). In this study, the highest crude protein of 21% was found in the sole cropped vetch, whereas the lowest crude protein content was in the triticale and ryegrass sole crops. Among the mixtures the 75% vetch: 25% triticale and 75% vetch: 25% ryegrass mixtures had significantly higher crude protein compared to the other mixtures with less vetch. The lowest ADF and NDF content was also found in the 75% vetch and 25% triticale mixture, whereas the highest NDF was in the sole cropped triticale and the 25% vetch and 75% triticale mixture. In this study, increasing the rate of cereal in the mixture increased the ADF and NDF levels, reducing the quality of forage (Carpici & Celik, 2014).

Likewise, in another two-year study in Turkey, the seed proportions at which oats and common vetch were intercropped were found to significantly affect the quality parameters of the forage. The highest crude protein content of 222.9g/kg was in sole cropped vetch while the lowest crude protein content of 84.8g/kg was in the sole cropped oats. Among the mixtures, the 15% oat: 85% vetch mixture had the highest crude protein content of 218.5g/kg and the lowest crude protein content of 99.4g/kg was in the 85% oat: 15% vetch mixture (Erol et al., 2009). Crude protein in this study increased with an increase in common vetch in the mixture.The NDF on the other hand significantly declined with an increase of vetch in the mixture, the lowest NDF content was in the 15% oat: 85% vetch mixture, whereas the highest NDF was in the 85% oat and 15% vetch mixture (Erol et al., 2009).

Likewise, a Malaysian corn-soybean intercrop study showed that the sowing proportion of the two crops in the mixture significantly affected forage quality parameters. Among the mixtures in this study, the highest crude protein content of 14.86% was in the 25% corn: 75% soybean mixture whereas the lowest crude protein content of 12.75% was in the 75% corn: 25% soybean mixture. For the ADF and NDF content, the highest values were in 75% corn: 25% soybean mixture. The ADF and NDF content increased with an increase in corn in the mixture, negatively affecting the quality of forage (Baghdadi et al., 2016). Again, in a 2-year pea-oat study in Turkey, the seed ratio affected the crude protein concentration of forage. In this study, the crude protein increased with an increase of pea in the mixture. The highest crude protein content of 15.5% was found in the 75% pea: 25% oat mixture whereas the lowest crude protein content of 13.85% was found in the 25% pea: 75% oat mixture (Uzun & Ferda, 2012). Likewise, in a vetch-cereal and pea-cereal study in Syria, the crude protein of mixtures increased with an increase of legume proportion in the mixture. In this study, the highest crude protein concentration was in the 66% legume: 33% cereal mixture, whereas the lowest crude protein concentration was in the 33% legume: 66% cereal mixture proportion (Osman & Nersoyan, 1986).

Similarly, in a two-year study in Pakistan, in which maize was intercropped with either cluster bean, cowpea, or sesbania, it was found that forage quality parameters were significantly affected by seeding ratios. In this study, crude protein and total ash were found to increase with an increase in legume in the mixture (Ibrahim et al., 2012). Likewise in a barley-pea study in the UK, it was found that the crude protein content and the digestible dry matter % was significantly affected by sowing proportions, these two parameters increased with an increase in the proportion of peas in the mixture, the highest being at 50% barley: 50% pea (Ayub et al., 2008). Similar results have also been found in a sorghum-rice bean study in Pakistan (Ayub et al., 2004), sorghum-lima bean study in Iran (Reza et al., 2012), and an oat-vetch study in Madagascar (Rahetlah, Randrianaivoarivony, Razafimpamoa, & Ramalanjaona, 2010).

However, increasing the legume proportion in an intercrop does not always improve the forage quality. In a study in Greece Dordas and Lithourgidis (2011), found that increasing the sowing rate of faba bean in faba bean-oat/triticale mixtures did not significantly increase the crude protein. In this study, there was no significant difference in crude protein content between the cereal monocrops and their respective intercrops. Similarly, in another study in Greece, in which triticale was intercropped with vetch, the ADF content was found to increase with an increase in legume in the mixture (Lithourgidis, Vasilakoglou, Dhima, Dordas, & Yiakoulaki, 2006). Differences in findings could be attributed to differences in the legumes used and their respective cultivars.

2.11 The pea crop

2.11. 1 General introduction

Peas are the 4th most important legume with an estimated production of 12 million tonnes of dry peas worldwide, cultivated on over 6,000,000 hectares (Comstock & Lothrop, 2011; Maxted & Bennett, 2001). Peas are an important component of the human diet in North America, Russia, Europe, China, and India and are rich in protein, fibre, and minerals (Maxted & Bennett, 2001). They have a wide range of varieties and are suited to a relatively wide range of agroecological environments, but the cultivation of the crop is mostly confined to temperate regions and higher altitudes, or the colder seasons of warmer regions (Comstock & Lothrop, 2011; Hebblethwaite, Heath, & Dawkins, 1985; Maxted & Bennett, 2001).

In agriculture, peas are classified as garden or field peas, based on utilisation; garden peas are used as green peas while field peas are used as dry peas (Newton, 1980; White & Hill, 1999).They are one of the least expensive crops to produce due to their ability to fix nitrogen in the soil (Comstock & Lothrop, 2011; Newton, 1980). Field peas (*Pisum sativum arvense* L.) are used for animal feed and play an important role in meeting the global demand for animal protein (Hebblethwaite et al., 1985; Maxted & Bennett, 2001). Peas have a low feeding value but they have a high crude protein content (Hebblethwaite et al., 1985).

2.11.2 Botany and growth requirements

Peas belong to the species *Pisum sativum* and the family *Fabaceae* (Ahmad, Anwar, & Hira, 2016). The leaf of a pea plant is a compound leaf that is made up of two to three pairs of leaflets followed by tendrils that allow the pea plant to climb (Khvostova, 1983; Meicenheimer & Muehlbauer, 1982). Peas have a tap root system that goes deep into the soil and has a large number of lateral roots (Khvostova, 1983; Meicenheimer & Muehlbauer, 1982). The roots of peas form nodules through which they can fix nitrogen in the soil through a process called biological nitrogen fixation (Cousin, 1997; Khvostova, 1983).

Biological nitrogen fixation is a process in which free-living and symbiotic cyanobacteria convert atmospheric nitrogen into a form useable by the plant, as a result of a symbiotic relationship in which the plant provides carbon to the bacteria (Bohlool, Ladha, Garrity, & George, 1992; Khvostova, 1983; Mus et al., 2016).

Peas have a round stem that is hollow, making the plant susceptible to lodging (Khvostova, 1983). They also have large green stipules which, like green pods, assist the pea plant with photosynthesis (White & Hill, 1999).Peas are self-pollinated plants (Cousin, 1997; White & Hill, 1999). The flowers vary dependent on the variety and can be white, pink, crimson, red-purple, or dark red-purple (Khvostova, 1983). "The fruit of the pea plant is made of two walls but develops from a single carpel that varies in shape as does the number of seeds in the pod" (Khvostova, 1983). Flowers in peas develop in a cluster of one or two, each flower produces a pod containing five to 12 ovules, with between two and ten of these developing into seeds (White & Hill, 1999). The seeds come in different shapes and can be round, oval, or slightly oval elongated and the seed surface can be smooth or wrinkled" (Khvostova, 1983; White & Hill, 1999).

Pea cultivars can either be determinate or indeterminate (White & Hill, 1999). In determinate pea cultivars, there is a clear distinction between vegetative and reproductive growth phases and the cultivars tend to be unbranched, with fewer nodes and they flower within a confined period (White & Hill, 1999). Indeterminate cultivars on the other hand have a terminal bud that is always vegetative and node and leaf production continue to occur after flowering for as long as growth conditions allow(Singh, 1981; White & Hill, 1999).The cultivars tend to have longer vines and a greater number of nodes and flowers (White & Hill, 1999). The grain yield of a pea crop is a factor of the plant population, number of pods per plant, number of seeds per pod, and individual seed weight (White & Hill, 1999).

Peas grow best in well-drained soils with good texture, aeration, and with a pH range of 6.0-6.5 (Hebblethwaite et al., 1985; Jermyn & Wratt, 1987; White & Hill, 1999). Where drainage is a problem, there is poor germination, high disease incidence, and poor nitrogen fixation (Newton, 1980). Peas are a cool temperate climate crop that do well in day temperature ranges of 8-12℃ minimum and 16-24℃ maximum (White & Hill, 1999). While peas are a cool climate crop, they are susceptible to frost, and frost during flowering and podding reduce yield (Newton, 1980). Peas have a low competitive ability against weeds and cultivars with long weak vines are susceptible to lodging (Jermyn & Wratt, 1987; Newton, 1980).

Peas are sensitive to drought and high temperatures and moisture supply is the major limiting factor for pea yield, the severity of this limitation is highly correlated to the level and timing of the moisture deficiency (Fougereux, Doré, Ladonne, & Fleury, 1997; Jermyn et al., 1993; White & Hill, 1999).

Moisture deficiency in peas affects canopy development and thus reduces the amount of photoactive radiation intercepted by the plant and reduces the crop duration (Jermyn & Wratt, 1987). On the other hand, extended periods of wet and cold weather have a negative impact on pea production as they provide a conducive environment for pea diseases (White & Hill, 1999). Pea growth and yield are dependent on the sowing dates and temperature, and later maturing cultivars tend to out yield early maturing cultivars (Fernandez, Sheaffer, Wyse, & Michaels, 2012; Newton, 1980).

2.11.3 Pea production in New Zealand

In New Zealand peas are the major grain legume, grown for both local consumption and export and have been grown since the beginning of arable farming (Jermyn & Wratt, 1987; Millner & Roskruge, 2013; White & Hill, 1999). They are important to the economy of the country, contributing 111.7 million NZD to the gross domestic product both directly and via pea dependent industries (Nixon, 2016).

They are usually sown in spring between August and October, but they can also be Autumn sown in May/June and overwinter in the rosette stage (White & Hill, 1999). Peas make a good break crop and their inclusion in wheat crop rotations not only help fix nitrogen in the soil but also improve soil structure, result in higher yields for the subsequent wheat crop and produce competitive gross margins (Greenwood et al., 2008). In New Zeeland, peas are grown on over 30,000 hectares per year, of which 70% of the total production is dry peas (White & Hill, 1999). Average yields of field peas are 3.5-3.8 tonnes per hectare but can be up to six tonnes per hectare where growth conditions are favourable (White & Hill, 1999). In recent years the pea industry in New Zealand was under threat due to the emergence of the pea weevil in 2016. The pest was however eradicated and no sightings of the pest have occurred since 2019 (Ministry of Primary Industries, 2022).

2.12 The oat crop

2.12.1 General introduction

Oats (*Avena Sativa* L.) are an important cereal crop in both developed and developing countries despite a drastic decline in production in the last 30 years (Baum, 1977; Webster, 2016). They are the sixth most-produced cereal after corn, wheat, barley, sorghum, and millet (Webster, 2016). Oats are a multipurpose crop that are used for industrial purposes, processed into various products for human consumption, and are also used in livestock production (Webster, 1986).

The use of oats for livestock production remains the primary use of oats accounting for about 74% of oat use worldwide (Stevens, Armstrong, Bezar, Griffin, & Hampton, 2004). Oats are used as forage and fodder, processed into hay or silage, and are used as bedding (Webster, 2016; White, Matthew, & Kemp, 1999). They are a nutritious source of feed and provide protein, fibre, and minerals to animals (Stevens et al., 2004; Webster, 2016). On average, 25% of the area under oats is cut for green feed (Webster, 2016).

2.12.2 Botany and growth requirements

Cultivated oats are annual grasses with stems that are made of nodes and internodes (Coffman, 1961). The leaves of oats are alternate and sessile and consist of the blade, the sheath, and the ligule (a membranous appendage)(Coffman, 1961). " The tillers of oats arise from the axils of foliage leaves on the oat plant" (Coffman, 1961). In oats, the root system is an adventitious root system that arises from the nods of the main stem (Brouwer & Flood, 1995; Coffman, 1961).

Oats are self-pollinated plants and the inflorescence in oats is a loose and open panicle (Coffman, 1961; Marshall & Sorrells, 1992), "oat spikelet's consist of two empty glumes on a rachilla which bears several flowers but usually, only the two basal flowers are fertile. The flowers consist of a lemma and palea, two lodicules, three stamen, and one pistil" (Coffman, 1961). “Oat grains are formed within a panicle which has a central rachis and spikelet’s at the tips of each branch” (White, Millner, & Moot, 1999).

Oat production lies between latitudes 35 and 65 ° N and 20 and 46 ° S and oats have been bred to adapt to a wide range of soils and climatic conditions (Barsila, 2018; Baum, 1977; Webster, 2016). They are mostly sown in spring, but can also be sown in Autumn in regions such as Australia and New Zealand (Webster, 2016). They do well in areas that receive adequate, but not excessive rainfall. The annual rainfall in oat-growing regions ranges from 38 to 114cm (Marshall & Sorrells, 1992). Oats grow well in cool moist climates and are susceptible to injury when the weather is hot and dry between head emergence and maturity (Baum, 1977; Coffman, 1961; Webster, 2016). As such, sowing must be scheduled to avoid higher temperatures towards maturity as these cause injuries and reduce production (Coffman, 1961; Webster, 2016). Drought during the vegetative stage results in slow culm growth, whereas drought at later stages mostly affects yield, and drought tolerance in oats varies from one variety to the other(Coffman, 1961).

Oats yield the highest in cool moist environments because they have a higher moisture requirement per unit of dry matter than other cereals and tend to be frost tolerant at seedling and tiller stages (Marshall & Sorrells, 1992; White, Millner, et al., 1999). Too much water however can restrict tillering in oats and reduce the length of roots and the leaf area index (Marshall & Sorrells, 1992).

Similar to other cereals, water stress in oats is particularly detrimental during reproductive growth stages especially at anthesis (Marshall & Sorrells, 1992).

Oats have lower nutrient requirements compared to other cereals and do well in well-drained soils with a pH of between 5.6-6.0 (Marshall & Sorrells, 1992; Webster, 1986; White, Millner, et al., 1999). They require about 25kg of nitrogen per tonne of grain yield (White, Millner, et al., 1999). Like other cereals, they respond positively to higher levels of nitrogen by increasing their vegetative growth and tiller production (Marshall & Sorrells, 1992).

Oat cultivars have different requirements for vernalisation and can be grouped into the following.

a) Spring types that do not respond to vernalisation
b) Intermediate spring-winter types that head more quickly in response to vernalisation
c) Winter types that respond to 28 days of vernalisation
d) Winter types that respond to 50 days of vernalisation
e) Stubborn types that do not respond to vernalisation (Marshall & Sorrells, 1992).

Oats are classified as long-day plants as many cultivars do not bear seeds in short-day environments and flowering is accelerated under long days (Marshall & Sorrells, 1992).

2.12.3 Oat production in New Zealand

Oats are an important field crop in New Zealand and of the oats produced, 70% is used in livestock feed, 25% is processed for human consumption (e.g. breakfast cereals and snacks) and 5% is used for seed (Millner & Roskruge, 2013; White, Millner, et al., 1999). Oats contribute 49 million NZD to the gross domestic product of the country both directly and via oat dependent industries (Nixon, 2016). Forage oats, which are mainly grown in winter, are used as green feed or silage and are fed to ewes, young cattle, hogget, and dairy cows (Millner & Roskruge, 2013; Newton, 1980). Oats are the preferred winter/spring green feed for livestock production in New Zealand as they produce significantly higher yields compared to wheat and barley (White, Matthew, et al., 1999).

Oats are also an important catch crop in New Zealand and have been found to significantly reduce nitrogen leaching and increase annual dry matter production when planted as a catch crop after winter grazing (Malcolm et al., 2018; Malcolm et al., 2017). Oats planted as a catch crop can produce up to10 tonnes dry matter yield of forage and allow for the uptake of up to 151.1kg/ha nitrogen as herbage N uptake, reducing the risk of nitrogen leaching (Malcolm et al., 2017).

The main oat-growing region is Canterbury. Oat yield in New Zealand ranges from 4.2-5.2 tonnes per hectare (White, Millner, et al., 1999).

2.13 Forage intercropping in New Zealand

A few forage intercropping studies have been conducted in New Zealand. A two-year study was conducted in Hastings to determine the optimum sowing time and the most suitable crop species to be intercropped with maize to increase forage yield and quality(Shaw et al., 2009). Another study was conducted in Christchurch to determine the feasibility of growing cereal-legume intercrops in between summer harvest and autumn planting to increase annual dry matter yield production (Fraser et al., 2004). However, no study has been conducted to determine the effect of intercropping on the yield and quality of forage oats and peas.

2.14 Literature review summary

The world's population continues to grow rapidly on otherwise static land whose productivity continues to diminish with use. Increasing crop production, therefore, hinges on improving productivity on limited land. Intercropping has shown a lot of potential in being a sustainable crop production system, through increasing water, nutrient, radiation capture, and use efficiency. This increase in capture and use efficiency of growth resources increases yields and improves the overall land-use efficiency, by allowing relatively more yield to be produced per unit area of land.

Intercropping also plays an important role in pest, disease, and weed control making it a powerful tool in organic crop production and integrated pest management systems. The changes in canopy structure, microclimate, and allelopathic effects of component crops enable intercrops to keep the incidence of pests, diseases, and weeds under control.

Intercropping is also very important in animal production. The mixing of forage legumes and cereals under intercropping allows for the improvement of yield and quality of forage. Cereals, while inherently having a high dry matter production potential, have low crude protein content and lower palatability and digestibility, while the opposite holds for legumes. Cereal-legume intercrops offer the potential to balance dry matter production and forage quality. However, the yield and quality of legume-cereal intercrops is dependent on the ratio at which the two crop species are sown in the field. Increasing the proportion of cereals increases the dry matter yield but reduces forage quality whereas increasing the legume proportion increases forage quality but reduces the dry matter yield. As such, determining the correct ratio at which legumes and cereals should be sown is very important in balancing forage yield and quality, both of which are very important for the farmer.

In New Zealand, very few studies have been done on forage intercropping. Specifically, no study has been conducted to determine the effect of intercropping on the yield and quality of forage oats and peas.

Chapter 3 : Materials and methods

3.1 Introduction

This chapter outlines the materials and methods used in this study. This includes the characteristics of the experimental site, the field layout and measurements, yield and quality traits determination, and data analysis.

3.2 Field experiment

This study was conducted to assess the effect of intercropping on the yield and quality of forage oats and peas using a mixed cropping replacement series intercropping design. Treatments consisted of sowing oats and peas at varying ratios. These ratios were percentages of the monoculture sowing ratios i.e., 150kg/ha for oats and 250kg/ha for peas**.** The treatments were as follows:

Table 3.1: Experimental treatments

Treatment number	Treatment description
Treatment 1	Peas grown as a pure stand (100% peas)
Treatment 2	Oats grown as a pure stand (100% oats) with Nitrogen
Treatment 3	Oats grown as a pure stand (100% oats) without Nitrogen
Treatment 4	50% Oats : 50% peas
Treatment 5	75% Oats : 25% peas
Treatment 6	25% Oats : 75% peas

Parameters measured in this study were the dry matter yield (DM) for both oats and peas, plant height of oats, leaf area index of each treatment, and the following forage parameters; metabolisable energy (ME), crude protein(CP), acid detergent fibre (ADF) and neutral detergent fibre (NDF). Two harvests were conducted, one at the booting stage and the other at the milky dough stage of the oats. Peas grown as a pure stand were only harvested once, at the first harvest. This is because the peas prematurely entered an advanced stage of senescence after the first harvest, a phenomenon likely caused by harvest injury as the peas were severely lodged.

3.3 Experimental site and environment

The experiment was conducted at the Pasture and Crop Research Unit (PCRU) No 1 Dairy Block, Massey University in Palmerston North, New Zealand (-40.381809, 175.606344). The soil type at this site is a Manawatū silt loam, a recent soil from alluvium proximate to the Manawatū River. The cropping history of the experimental site was winter sown oats, in 2019.

Soil sample analysis was done in the 0-15cm profile, and the chemical breakdown was as follows:

Table 3.2: Chemical analysis of the soil at the trial site, 0-15cm.

Nutrient	Amount (mg/Kg)
Phosphorus	46
Potassium	148.58
Calcium	880
Magnesium	147.62
Sodium	18.4

Chemical analysis of the soil showed adequate phosphorus levels, as such none was applied. Nitrogen was applied in treatment 2 only and it was applied at a rate of 46kg N/ha, on 11 September 2020, 108 days after planting**.** The fertiliser was not applied at sowing in this trial due to the late winter planting. This was to avoid leaching of the nutrients and to target a time when the fertiliser would be adequately used by the crop. The field was cultivated to prepare a desirable seedbed. No weeding was done within the experimental plots and no pesticides were used.

3.4 Plant materials

One oat and one pea variety were used in this trial and the details of each crop variety are as below.

3.4.1 Milton oats

Milton oats are a high-yielding variety bred in New Zealand using select lines from the United States of America. It has a high stem-to-leaf ratio, is disease resistant, and is highly suitable for autumn planting and single grazing (Agricom, 2020).

3.4.2 Secada peas

Secada is a US-bred forage pea that is relatively new, it has a wide range of uses including green manure. It is a self-climbing pea variety with a high dry matter yield, and it is highly palatable. It is a fast-growing cultivar and grows well in autumn, winter, and spring (Oregro-Seeds, 2020).

3.5 Field experiment layout

Trial treatments were arranged in a randomised complete block design which consisted of three replicates, where each block represented a replicate. Each plot measured 5m by 1.5m, with a row spacing of 15cm, and had an area of 7.5m^2.

The experiment was sown on 26 May 2020, which was late sowing due to lockdown restrictions as a result of the Covid-19 pandemic. Sowing was done using a cone seeder plot drill, which is recommended for sowing small quantities of seeds on small plots with short rows, as was the situation with this trial (Copp & Lawson, 1970).

3.6 Field measurements

After sowing, a germination count was conducted to ensure the successful establishment of the crop. This involved the counting of germinated plants along a 100cm length of four randomly selected rows in each plot and calculating germination percentage.

Plant height was measured at harvest 1 (when 75% of the field was at the booting stage, 157 days after planting) and harvest 2 (when 75% of the field was milky dough stage, 183 days after planting). Plant height was measured from the base of the stem to the ligule of the flag leaf.

Plate 3.1: Measuring the height of oat plants

Leaf area index was measured at 143 days after planting (when the last leaf was visible) and at the milky dough stage (183 days after planting). Leaf area index (LAI) was measured using LAI-2200C Plant Canopy Analyser. It involved taking one reading above the crop canopy and four readings below the canopy. The below-ground readings were at four randomly selected points that formed a diagonal transect within the plot.

The plant canopy analyser computed the LAI using the above and below canopy readings (Danner, Locherer, Hank, Richter, & Consortium, 2015). For each plot, three LAI measurements were taken, and an average was calculated.

The first harvest was conducted when 75% of the field was at the booting stage, 157 days after planting. The net plot was 4.5m^2 and harvest was done on 4 randomly selected 100cm rows in each plot. Forage was cut at the bottom of the stem and in the mixed plots, pea and oat plants were separated. Harvested plants were immediately transported to the lab for weighing to prevent water loss. The second harvest was done when 75% of the field was at the milky dough stage, 183 days after planting and the same procedure was followed.

3.7 Laboratory procedures

The following lab procedures were carried out to determine yield quantity and quality.

3.7.1 Yield determination

The fresh weight of forage for each treatment was weighed. In the mixed treatments, the weight of oats and peas were recorded separately and for peas, the weight of pods was recorded separately from the rest of the plant. A sub-sample of 300g was weighed from each plot and dried in a forced-air oven set at 70℃ for 72 hours, or until no more weight loss occurred (Newton, 1980). In the case of pea plants, where some plots did not have enough plant material for a 300g sub-sample, a 100g subsample was used for drying. The dry matter percentage was calculated as below:

Dry matter % = (Oven dry weight/ Fresh weight) x100 (Newton, 1980)

The yield of each treatment was calculated from the dry matter percentage. For the mixed treatments, the total yield of each harvest was the combination of the oat and pea yield.

Plate 3.2: Weighing pea pods for dry matter determination.

Plate 3.3: Weighing oat plants for dry matter determination.

3.7.2 Forage quality

Forage samples were ground to 1mm size using a Cyclotec 1093 laboratory mill**.** Peas and oats were ground separately. 20g of forage of each sample was sent to the Massey University Nutrition Laboratory for quality analysis, the parameters analysed were the nitrogen percentage from which crude protein (CP) was calculated, acid detergent fibre (ADF), neutral detergent Fibre(NDF), and the metabolisable energy (ME).

The percentage nitrogen was determined using a Rapid Max N exceed machine, which uses the dumas method for protein determination (Ebeling, 1968). The Van Soest detergent method was used to determine the ADF and NDF of forage samples using a Fibretec System (FOSS-Tecator) (Pereira-Lorenzo, Ramos-Cabrer, Díaz-Hernández, Ciordia-Ara, & Ríos-Mesa, 2006; Van Soest, Robertson, & Lewis, 1991). The metabolisable energy of samples was determined using a pepsin-cellulose assay method of analysis (Goto & Minson, 1977; McLeod & Minson, 1982; Roughan & Holland, 1977). Crude protein yield and metabolisable energy yield were also calculated.

3.8 Evaluation indices calculations

The land equivalent ratios for each intercropped treatment was calculated using the following formula:

$(IC_a/M_a) + (IC_b/ M_{b)}$ + …… $(IC_n/ M_{n)}$

Where:

IC is the intercrop biomass and M is the monoculture biomass and ‘a’, ‘b’, ‘n’, are the species.

The competitive ratios of each crop were calculated using the following formula:

$CR_a= (LER_a/LER_b) (Zb_a/Za_b)$

Where:

CR_a is the competitive ratio of crop ‘a’.

LER_a and LER_b are the land equivalent ratios of crop ‘a’ and crop ‘b’ respectively.

Zb_a and Za_b are proportions of surface area occupied at sowing by crop ‘a’ and crop ‘b’ respectively.

The land equivalent ratios and the competitive ratios were only calculated for harvest 1 due to the premature death of the pea plants by the second harvest as explained above and the calculations used monoculture biomass of fertilised oats.

3.9 Statistical analysis

Data was analysed using R statistical package and a 2-way analysis of variance (ANOVA) was used to analyse the dry matter yield, leaf area index, plant height, CP, ADF, NDF, ME, crude protein yield, metabolisable energy yield, competition ratio, and land equivalent ratios (LER). Means were separated using Tukey's honest significant difference test (HSD) at P=0.05.

Linear regression was used to determine the relationship between the yield, metabolisable energy, and crude protein content. The first and second harvests were analysed separately, and the yield of oats and peas was also analysed separately.

In this study, the model used for statistical analysis was as follows:

$Y_{ijk} = \mu + A_i + B_j + E_{ijk}$

Where,

Y_{ijk} is the i^{th} observation in the i^{th} treatment group and j^{th} block.

μ is the general mean.

A_i is the treatment (sowing ratio) effect.

B_j is the blocking effect.

E_{ijk} is the random residual error.

$i = 1\text{-}6$

$j = 1\text{-}3$

Plate 3.4: Healthy pea plants before lodging

Plate 3.5: Severely lodged peas which become intertwined making harvesting difficult

Plate 3.6: Pea plants in early senescence after the first harvest

Plate 3.7: A pea plant thrives among oats in a mixed treatment

Chapter 4 : Results

4.1 Introduction

Chapter 4 describes the results of this study. It presents the prevailing weather conditions under which the experiment was conducted, the dry matter yield data, the forage quality data, including crude protein content, fibre, and metabolisable energy (ME) for two harvest dates. Agronomic parameters including plant height and leaf area index are also presented.

4.2 Weather

The mean rainfall and temperature data for the year 2020 in Palmerston North, New Zealand is presented in Table 4.1.The experimental trial for this research carried through two seasons, winter and spring. The winter growing season for 2020 was relatively dry and warm (Table 4.1). The rainfall for the season was lower than the long-term mean, and the temperatures were higher than the long-term mean. The mean temperature for June 2020 was 2.4 °C higher than that of the long term mean for the month, and the mean temperatures for May and July were 0.4°C and 0.5°C higher than the long term means of their respective months. For spring, September 2020 was wetter than the long-term mean, whereas the rainfall for August and October was lower than the long-term mean. Temperatures for spring were also higher than the long-term mean. The mean temperature for October 2020 was 1.2 °C higher than the long term mean for the month, and the mean temperatures for August and September were 0.9°C and 0.1°C higher than the long term means for their respective months

Table 4.1: Monthly rainfall (mm) and temperature (°C) for Palmerston North in 2020, compared to the long-term means, 1981-2010.

(National Institute of Water and Atmospheric Research, 2020).

	May	June	July	August	September	October	November
Monthly Rainfall 2020	66.4	64.4	65	40	137.6	63	107.4
Rainfall long term Mean	83.2	96.9	88.3	79.7	86	94.5	79.5
Monthly Temperature 2020	11.9	11.7	9.2	10.3	11.1	13.7	15.2
Temperature long term Mean	11.5	9.3	8.7	9.4	11	12.5	14.2

4.3 Forage dry matter yield

In harvest 1, there were no differences in oat yield among the treatments (Table 4.2). The highest oat yield of 15,527 kg/ha was produced in the sole cropped fertilised oats (treatment 2), the lowest oat yield was treatment 4 (50% oats: 50% peas), which produced a yield of 12,563kg/ha. There was a significant difference in pea yield among the treatments (Table 4.2). The highest pea yield was in the sole cropped peas which produced a yield of 5,930kg/ha, which was followed by the pea yield produced in treatment 6 (25% oat: 75% pea) and was not significantly lower. The lowest pea yield (1,377kg/ha) occurred in treatment 5 (75% oat and 25% pea). For the total dry matter yield, the sole cropped peas had a significantly lower yield than all other treatments, which were not significantly different from each other (Table 4.2).

Table 4.2: Forage dry matter yield for harvest 1 (75% oat booting stage), 157 days after sowing

	Dry matter yield (kg/ha)		
Treatment	Oat yield	Pea yield	Total yield
1 (100% peas)		5930a	5930 b
2 (100% Oats with Nitrogen)	15527 a		15527 a
3 (100% Oats without Nitrogen)	15321 a		15321 a
4 (50% Oats:50% Peas)	12562a	1521b	14083 a
5 (75% Oats:25% Peas)	13873a	1377b	15250 a
6 (25 Oats:75% Peas)	13334a	2489a	15823 a
Significance	NS	0.001	0.001

Means with the same letter within the same column are not significantly different at P = 0.05

Harvest 2 has no sole cropped pea dry matter yield data as the pea plants in this treatment were in an advanced state of senescence (Chapter 3). At harvest 2, oat yield did not significantly differ among the treatments (Table 4.3). There was a significant difference in pea dry matter yield; treatment 6 (25% Oats: 75% Peas) had a significantly higher pea dry matter yield than treatments 4 and 5.

Total dry matter yield was also influenced by treatment at the 2nd harvest (Table 4.3). The highest dry matter yield was produced by treatment 6 (25% oats:75% peas), with a yield of 21,110kg/ha, whereas the lowest yield was in the sole cropped unfertilised oats (14, 353kg/ha). In this harvest, only treatment 6 outyielded the sole cropped unfertilised oats.

Table 4.3: Forage dry matter yield for harvest 2 (75% milky dough stage),183 days after sowing

	Dry matter yield (kg/ha)		
Treatment	Oat yield	Pea yield	Total yield
1 (100% peas)			
2 (100% Oats with Nitrogen)	16690a		16690 ab
3 (100% Oats without Nitrogen)	14353a		14353 b
4 (50% Oats: 50% Peas)	14781a	1629b	16410 ab
5 (75% Oats:25% Peas)	13510a	1375b	14885 ab
6 (25 Oats:75% Peas)	15015a	6095a	21110 a
Significance	NS	0.01	0.05

Means with the same letter within the same column are not significantly different at P = 0.05

4.4 Leaf area index

There were no significant treatment differences in leaf area index (LAI) for both harvests 1 and 2 (Table 4.4). At harvest 1 the leaf area index ranged from 4.27(treatment 3, sole cropped unfertilised oats) to 5.67(treatment 6, 25% oats:75% peas) while at harvest 2 it ranged from 3.57(treatment 3) to 4.38 (treatment 2).

4.5 Oat plant height

Oat plant height was not influenced by treatment at either harvest date (Table 4.4). At harvest 1, plant height ranged from 113cm (treatment 6, 25% oats: 75% peas) to 121cm (treatment 2, fertilised sole cropped oats) . In contrast, at the 2nd harvest, plant heights ranged from (124cm) in treatment 3 to 132cm (treatment 6) .

Table 4.4: Analysis of leaf area index and oat plant height for harvest 1 and 2

	LAI		Oat plant height (cm)	
Treatment	Harvest 1	Harvest 2	Harvest 1	Harvest 2
1 (100% peas)	4.60 a	.	.	.
2 (100% Oats with Nitrogen)	5.17 a	4.38 a	121 a	127 a
3 (100% Oats without Nitrogen)	4.27 a	3.57 a	118 a	124 a
4 (50% Oats: 50% Peas)	4.40 a	3.80 a	109 a	125 a
5 (75% Oats: 25% Peas)	5.17 a	3.98 a	115 a	127 a
6 (25 Oats: 75% Peas)	5.67 a	4.01 a	113 a	132 a
Significance	NS	NS	NS	NS

Means with the same letter within the same column are not significantly different at P = 0.05

4.6 Forage quality

All forage quality parameters were significantly affected by treatment at harvest 1 (Table 4.5). The highest crude protein content (17.45%) was recorded in the sole cropped peas, while the lowest crude protein content (5.95%) occurred in the sole cropped unfertilised oats. The sole cropped peas, and all the mixtures, had significantly higher crude protein contents than the sole cropped fertilised and unfertilised oats.

The highest ADF content was found in the sole cropped unfertilised oats (treatment 3) (44.3%) while the lowest ADF content (27.3%) occurred in the sole cropped peas (treatment 1). The NDF content followed a similar pattern, the highest being in treatment 3 (70.7%) and the lowest (41.6%) in the sole cropped peas.

Metabolisable energy content reflected the differences in fibre content, the highest occurring in treatment 1 (10.74 MJ/kg) and the lowest in Treatment 3 (8.76 MJ/kg).

Table 4.5: Crude protein, Acid Detergent Fibre (ADF), Neutral Detergent Fibre (NDF), and metabolisable energy (ME) content of forage at harvest 1(75% oat booting stage), 157 days after sowing

Treatment	Crude protein (%)	ADF (%)	NDF%	ME (MJ/kg)
1 (100% peas)	17.45a	27.3b	41.6c	10.74a
2 (100% Oats with Nitrogen)	8.08c	42.7a	70.5a	8.91b
3 (100% Oats without Nitrogen)	5.95c	44.3a	70.7a	8.76b
4 (50% Oats: 50% Peas)	13.88ab	33.1b	51.3b	10.16ab
5 (75% Oats: 25% Peas)	13.24b	31.0b	46.4bc	9.19ab
6 (25 Oats:75% Peas)	15.39ab	32.1b	50.5bc	10.22ab
Significance	0.001	0.001	0.001	0.01

Means with the same letter within the same column are not significantly different at P = 0.05

At the 2nd harvest, only crude protein content and NDF were significantly affected by treatments (Table 4.6). The highest crude protein content was found in treatment 6 (8.81%) while the lowest crude protein content (5.02%) occurred in treatment 3. NDF content was highest in treatment 3 (74.4%) and the lowest in treatment 6 (67.6%).

The ADF and metabolisable energy were not significantly affected by treatments (Table 4.6). ADF ranged from 51.4% down to 45.0%. ME energy content showed very little variation (range 8.54 MJ/kg to 8.27MJ/kg).

Table 4.6: Crude protein, ADF, NDF, and ME content of forage at harvest 2 (75% milky dough stage),183 days after sowing

Treatment	Crude protein (%)	ADF (%)	NDF (%)	ME (MJ/kg)
1 (100%peas)				
2 (100% Oats with Nitrogen)	5.80b	45.0a	71.6ab	8.36a
3 (100% Oats without Nitrogen)	5.02b	51.4a	74.4a	8.27a
4 (50% Oats: 50% Peas)	7.34ab	50.4a	70.3ab	8.43a
5 (75% Oats:25% Peas)	7.12ab	51.2a	71.0ab	8.35a
6 (25 Oats:75% Peas)	8.81a	47.8a	67.5b	8.54a
Significance	0.001	NS	0.05	NS

Means with the same letter within the same column are not significantly different at P = 0.05

At harvest 1, the crude protein and metabolisable energy yield were significantly affected by treatments (Table 4.7). Crude protein yield was highest in treatment 6 (2,435 kg/ha) while the lowest crude protein yield was in the sole cropped unfertilised oats (treatment 3) (910 kg/ha). Similarly, the sole cropped peas had significantly lower metabolisable energy yield (63586 MJ/ha) compared to the remaining treatments, which were not significantly different, having ME yields ranging from 13,8430 (treatment 3) to 16,1138 MJ/ha (treatment 6). Crude protein and ME yields were also significantly affected by treatments at harvest 2 (Table 4.7). The highest crude protein and ME yields occurred in treatment 6 (1,865kg/ha and 118,653 MJ/ha respectively) while the lowest occurred in treatment 3 (7,31kg/ha and 18,0384 MJ/ha respectively).

Table 4.7: Crude protein yield and metabolisable energy yield at harvest 1 and 2

	Crude protein yield (kg/ha)		ME yield (MJ/ha)	
Treatment	Harvest 1	Harvest 2	Harvest 1	Harvest 2
1 (100%peas)	1040c	.	63586b	.
2 (100% Oats with Nitrogen)	1263bc	981b	138430a	139412ab
3 (100% Oats without Nitrogen)	910c	731b	134237a	118653b
4 (50% Oats:50% Peas)	1996ab	1224ab	142005a	138195ab
5 (75% Oats: 25% Peas)	2023ab	1058b	140304a	124042b
6 (25 Oats: 75% Peas)	2435a	1865a	161138a	180384a
Significance	0.001	0.01	0.01	0.05

Means with the same letter within the same column are not significantly different at P = 0.05

Table 4.8: Mean crude protein yield (kg/ha) and mean metabolisable energy (ME) yield (MJ/ha) for harvest 1 and 2

	Mean crude protein yield (kg/ha)	Standard Error	Mean metabolisable energy (MJ/ha)	Standard Error
Harvest 1	1,725.23	177.66	122,392.13	6,047.29
Harvest 2	1,171.62	118.08	115,547.56	6,744.56

Mean crude protein and metabolisable energy yields were calculated using treatment 2 to 6 only.

Crude protein yield and metabolisable energy yield were both higher at harvest 1 compared to harvest 2

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4.7 Relationship between yield, metabolisable, and crude protein content

Regression analysis of ME content and dry matter yield across all treatments (Figure 4.1), revealed a moderately negative relationship between them. As yield increased, ME content declined. However, the regression analysis of ME content and dry matter yield of oats alone (Figure 4.2) produced a produced marginally stronger negative relationship (R^2 =0.41). Crude protein content was also weakly negatively related to total dry matter yield (Figure 4.3); restricting the analysis to oats only strengthened the relationship (Figure 4.4).

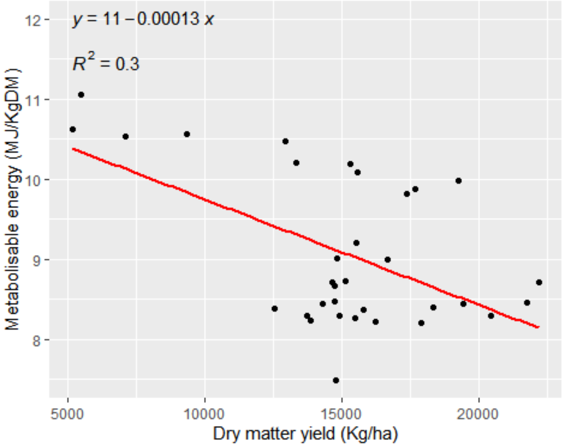

Figure 4.1: Regression analysis of metabolisable energy and dry matter yield

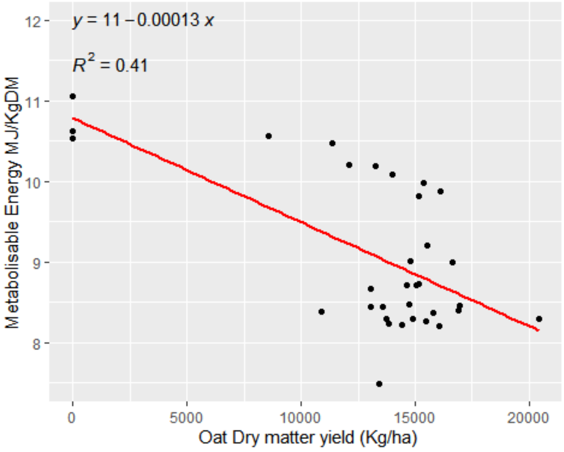

Figure 4.2: Regression analysis of metabolisable energy and oat dry matter yield

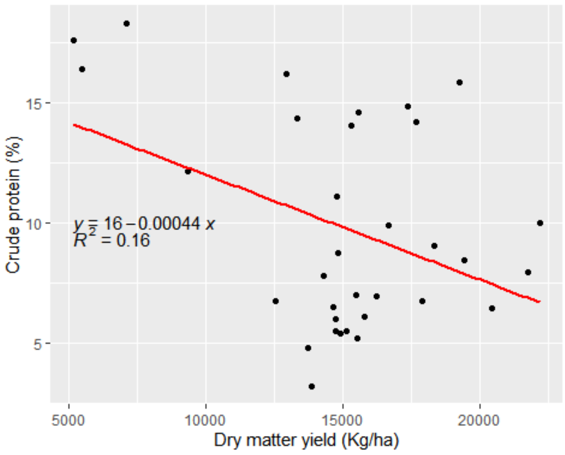

Figure 4.3: Regression analysis of crude protein and dry matter yield

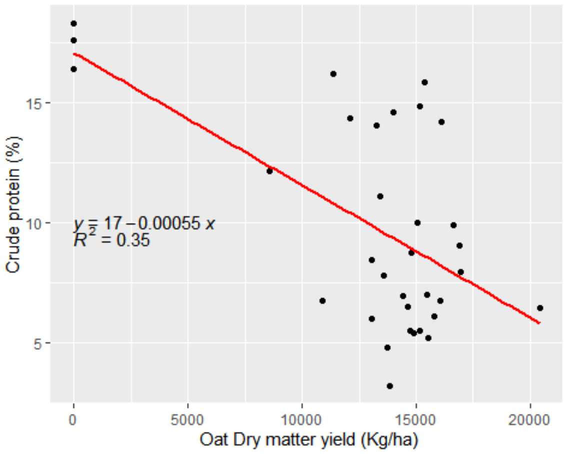

Figure 4.4: Regression analysis of crude protein and oat dry matter yield

4.8 Evaluation of the intercropping system

Due to pea plants being in an advanced stage of senescence at harvest 2, competition and land equivalent ratios (LER) were only calculated for harvest 1. The LER of the three mixtures in harvest 1 were similar (Table 4.8). There was a significant difference in the oat competition ratio and the pea competition ratio (Table 4.8).

The highest oat competition ratio (6.66) was found in treatment 6 and the lowest (1.28) in treatment 5 (75% oat: 25% pea). For the peas, the highest pea competition ratio (0.627) was found in treatment 5, and the lowest pea competition ratio (0.103) in treatment 6.

Table 4.9: Land equivalent ratios (LER) and competition ratios (CR) for harvest 1

Treatment	LER	CR OAT	CR PEA
1 (100%peas)			
2 (100% Oats with Nitrogen)			
3 (100% Oats without Nitrogen)			
4 (50% Oats: 50% Peas)	1.06a	3.32b	0.307b
5 (75% Oats:25% Peas)	1.12a	1.28b	0.627a
6 (25 Oats: 75% Peas)	1.26a	6.66a	0.103c
Significance	NS	0.01	0.001

Means with the same letter within the same column are not significantly different at P = 0.05

Chapter 5 : Discussion

5.1 Introduction

This chapter discusses the results of the study. The discussion covers the influence of different treatments on forage yield and quality and compares this with results from previous research. It also outlines the implications of this research to farmers in New Zealand.

5.2 Forage dry matter yield

In harvest 1, there were no significant differences in the oat yield between any of the treatments. This could be attributed to high soil fertility (Table 3.2), which enabled the non-fertilised plots to perform just as well as the fertilised plot; yield responses to nitrogen in cereals under moderate to high soil fertility conditions may be poor (Huang et al., 2017). The highest pea dry matter yield was produced in the sole cropped pea followed by the 25% oat: 75% pea treatment. The pea yield in harvest 1 increased as pea proportion increased (Kocer & Albayrak, 2012; Osman & Nersoyan, 1986).

The sowing ratios significantly affected the total dry matter yield (Ayub et al., 2004; Baghdadi et al., 2016; Carpici & Celik, 2014; Lithourgidis & Dordas, 2010; Uzun & Ferda, 2012). Sole-cropped peas produced a significantly lower dry matter yield than all other treatments. Many researchers in oat and pea intercropping studies at various sowing ratios have found that dry matter yields are lowest in sole cropped peas (Droushiotis, 1989; Tsialtas, Baxevanos, Vlachostergios, Dordas, & Lithourgidis, 2018; Uzun & Ferda, 2012). The highest total dry matter yield was found in treatment 6 (25% Oat: 75% pea), which could be attributed to relatively high spatial complementarity, which allowed the component crops of the mixture to exploit different soil layers, increasing the overall productivity (Willey, 1979).

Findings from this study are similar to research findings by Dhima et al. (2014) who found the dry matter yield of sole cropped oats to not be significantly different from the dry matter yield of oat and faba bean mixtures. They are also similar to those of Ayub et al. (2004) who found the dry matter yield of sole cropped sorghum to not be significantly different from the dry matter yield of sorghum-rice bean mixtures. However, other researchers found that higher dry matter yield was produced in sole cropped oats, rather than oat-pea intercrops (Droushiotis, 1989; Tsialtas et al., 2018; Uzun & Ferda, 2012). These contrasting results could be attributed to differences in climatic and soil fertility conditions. Climate influences the level of complementarity in intercropping systems (Anil, Park, Phipps, & Miller, 1998).

Also, the effects of complementarity tend to be higher under low-input systems compared to systems where inputs are not limiting (Anil et al., 1998).

In harvest 2, treatment 6 was significantly higher than treatment 3, though it was not significantly different from the rest of the treatments. This could be attributed to a relatively higher complementarity in the mixture. These findings are in line with findings by Osman and Nersoyan (1986) who found that the treatment with the highest pea proportion outyielded unfertilised sole cropped oats. Since there was no significant difference in the oat yield in both harvests, the significantly higher yield of treatment 6 in harvest 2 can be attributed to the relatively high pea yield at this harvest (Table 4.3). In general, there was a higher dry matter yield in harvest 2 than in harvest 1. This is expected, as dry matter yield increases with crop maturity (Mevlüt & Albayrak, 2012; Uzun & Ferda, 2012).

5.3 Leaf area index

In both harvests 1 and 2, the sowing ratios did not significantly affect the leaf area index. The lack of significant difference among the sole crops and mixtures is in line with findings by Dhima et al. (2014) working with oat and faba bean mixtures. However, these findings are contrary to those of Carpici and Celik (2014), who found significant differences in the leaf area index of sole crops and mixtures when common vetch was intercropped with either rye or triticale. Differences in these findings could be attributed to the growth habits of the cereals and legumes used in the studies. It has been found that the effects of intercropping on leaf area index vary according to the component crops, as they influence canopy structure and shading (Ghosh, 2004; Keating & Carberry, 1993).

Treatment 1 (100% peas) did not have the lowest LAI despite having the lowest yield, this could be attributed to the inherent low dry matter yield potential of legumes (Kocer & Albayrak, 2012; Nadeem et al., 2010; Osman & Nersoyan, 1986). The low yield potential of legumes can be attributed to legume tissue being composed mainly of protein, whereas in cereals the vegetative tissue is mainly made up of carbohydrates (Ruckle et al., 2017; Sinclair, 2004). As such even though its leaf area index was relatively high, its intrinsic yield potential resulted in a lower dry matter yield. The high carbohydrate content is what makes cereals high-energy forage compared to legumes (Eskandari et al., 2009).

The lack of significant difference in the leaf area index indicates that there was no difference in the interception of photoactive radiation among the mixtures and sole crops (Vasilakoglou & Dhima, 2008).

Consequently, the significant yield difference between the sole cropped unfertilised oats and the 25% oats:75% pea treatment is most likely the result of nutrient complementarity and not an increase in radiation capture and use efficiency.

5.4 Oat plant height

The plant height of oats in both harvests 1 and 2 was not affected by treatment mixtures. This could be attributed to the lack of aggressive growth and poor competition of peas in comparison with cereals, as seen from the competition ratios (Table 4.8), (Jermyn & Wratt, 1987; Newton, 1980). These findings are in line with findings by Dordas and Lithourgidis (2011), who found that there was no significant difference in the height of either oat or triticale when grown as a sole crop or in combination with faba bean. Similarly, Lithourgidis and Dordas (2010) found no differences in the height of cereals (wheat, barley, and rye) when grown as sole crops or intercropped with faba bean. However, these results are contradictory to findings by Ibrahim et al. (2014) who found that the height of maize was reduced when the cereal was intercropped with sesbania, due to the aggressive growth habit of the legume. The differences in findings can be attributed to the differences in the competitiveness of the legumes used.

5.5 Forage quality

In harvest 1, all forage quality parameters were affected by seed ratio treatments. Sole cropped peas had the highest crude protein content of 17.45%, whereas the lowest crude protein was in the sole cropped unfertilised oats, with a crude protein content of 5.95%. This is consistent with other research comparing the effect of seeding ratios of oats and peas on crude protein (Ayub et al., 2008; Droushiotis, 1989; Osman & Nersoyan, 1986; Tsialtas et al., 2018; Uzun & Ferda, 2012). This is a result of the high protein content of peas, a legume, compared with cereals. The crude protein content of all the mixtures was significantly higher than the crude protein of the sole cropped oats, peas increased the crude protein content of mixtures since peas are naturally high in crude protein (Ayub et al., 2008; Droushiotis, 1989; Osman & Nersoyan, 1986; Uzun & Ferda, 2012). Among the mixtures, the increase in pea proportion did not result in a significant increase in the crude protein content (Dordas & Lithourgidis, 2011; Lithourgidis, Vlachostergios, et al., 2011).

The lowest ADF and NDF were in sole cropped peas, while the highest ADF and NDF were in the sole cropped oats, consistent with previous research (Begna et al., 2011). All mixtures also produced forage with significantly lower ADF and NDF content compared to sole cropped oats (Kocer & Albayrak, 2012).

This is due to the presence of peas in the mixtures, as legumes generally have lower ADF and NDF content compared to cereals (National Research Council, 2001). These findings indicate that mixtures produced superior forage compared to sole cropped oats, as low ADF and NDF increase forage intake and digestibility (Eskandari et al., 2009).

Sowing ratios also significantly affected the metabolisable energy content. The metabolisable energy of forage is an important quality parameter as it indicates the available energy, which in turn affects livestock productivity (Moran, 2005; Waghorn, 2007). Sole cropped peas had significantly higher metabolisable energy than sole cropped oats. The higher metabolisable energy in the sole cropped peas can be attributed to higher digestibility; this treatment had the lowest ADF and NDF levels, associated with increased digestibility of forage and consequently higher metabolisable energy (Moran, 2005; Suha Uslu, Kurt, Kaya, & Kamalak, 2018). All mixtures also had relatively higher metabolisable energy content compared to the monocrop oats, due to the presence of peas.

Except for treatment 6, (25% oats: 75% peas) and the sole cropped unfertilised oats, there were no differences in crude protein and NDF at harvest 2. Similarly, the sowing ratio did not affect ADF and metabolisable energy. Other researchers, J. Jacobs and Ward (2008) also found no differences in the crude protein, metabolisable energy, and NDF when triticale-pea mixtures were harvested at a later stage in the cereal growth cycle (soft dough stage). However other researchers have found that intercrops of peas and oats had significantly higher crude protein content and lower ADF and NDF levels (Ayub et al., 2008; Begna et al., 2011; Droushiotis, 1989; Osman & Nersoyan, 1986; Tsialtas et al., 2018; Uzun & Ferda, 2012). The difference in findings could be attributed to differences in the growth stage of peas at the time of harvest. The late winter planting in this study extended the growth period of the oats and resulted in the second harvest occurring when peas were past maturity. This in turn reduced the contribution of crude protein and increased the ADF and NDF levels, since crude protein is negatively correlated with plant age (Stokes & Prostko, 1998), and the need for structural tissue also increases with age (Borreani, Peiretti, & Tabacco, 2007).

The sowing ratios also significantly affected the crude protein yield. In harvest 1 the crude protein yield was significantly higher in all three mixture treatments compared to the sole cropped peas, despite having the highest percentage of crude protein. This is a result of the low yield in the sole cropped peas, (Dordas & Lithourgidis, 2011).

Crude protein yield results at harvest 1 are similar to those by Dordas and Lithourgidis (2011) and Lithourgidis, Vlachostergios, et al. (2011), who also found that while the mixture with the highest legume proportion had the highest crude protein yield, mixtures with a lower legume proportion had crude protein yields that were not significantly different from the sole cropped cereal. The high crude protein yield in treatment 6 could be attributed to its relatively high dry matter production (Table 4.2) coupled with its relatively high crude protein content (4.5). These results contrast those by other researchers, Dordas, Vlachostergios, and Lithourgidis (2012) and Osman and Nersoyan (1986) who found that all mixtures had significantly higher crude protein yields than sole cropped cereals. Differences in these studies can be attributed to differences in dry matter yield and crude protein content since crude protein yield is a factor of these two parameters.

The crude protein yield at harvest 2 followed a similar pattern; only the crude protein yield from treatment 6 was significantly higher than that of the sole cropped oats, whereas the other two mixtures were not significantly different from the sole cropped oats. This could be attributed to the significantly higher dry matter production in treatment 6 (Table 4.3) coupled with its significantly higher crude protein content (4.6) in comparison to the sole cropped oats.

The metabolisable energy yield was also significantly affected by the seeding ratios at both harvests. In harvest 1, sole cropped peas had significantly lower metabolisable energy yield compared to remaining treatments, which were not significantly different from each other. This is also the result of the low dry matter yield in this treatment. A high metabolisable energy content is insufficient to overcome the disadvantage of low dry matter yield. The lack of significant difference in the metabolisable energy yield among the 5 treatments in harvest 1 reflects the similarity in both metabolisable energy content (Table 4.5) and yields (Table 4.2). At harvest 2, the high ME yield of treatment 6, is a result of high yield (Table 4.3) rather than higher metabolisable energy content (Table 4.6).

A comparison of the mean crude protein yield and the mean metabolisable energy yield (Table 4.8) showed that there was a higher crude protein and metabolisable energy yield at harvest 1 than at harvest 2. This is because crude protein and metabolisable energy decline with the age or development of the crop (Arzani et al., 2004; Stokes & Prostko, 1998).

5.6 Evaluation of the intercropping system

There were no differences in the land equivalent ratios among the mixtures. All the mixtures had a land equivalent ratio of greater than 1, indicating intercropping advantage. The land equivalent ratios indicated that 26%, 12%, and 6% more land would be required under sole cropping to produce the equivalent dry matter yield produced in treatments 6, 4, and 5 respectively. These findings are similar to findings by other researchers who found intercropping legumes and cereals to have a yield advantage, as shown by LERs of greater than 1 (Javanmard et al., 2009; Lithourgidis, Vlachostergios, et al., 2011; Yilmaz et al., 2008). However, these findings are contradictory to (Jalilian et al., 2017) who found intercropping to have no yield advantage. Differences in findings can be attributed to differences in the complementarity of the component crops since that determines the performance of an intercropping system.

There were significant differences in the competition ratio of oats among the mixtures. All the competition ratios for oats in mixtures were greater than 1, indicating that oats had a negative effect on the growth of the peas. There was a significant difference in the competition ratio of peas in mixtures, but none of them were greater than 1, indicating that peas can be grown in combination with other crops, as they didn't negatively affect the oat growth in this study. These findings are similar to those of Dhima et al. (2014) who found the competition ratio of faba bean to be less than 1, whereas the competition ratio of oats was greater than 1 in an oat-faba bean intercrop study. The above findings were expected as cereals tend to be more competitive than legumes.

5.7 Implications of these research findings for farmers in New Zealand

Only treatment 6 (25% oats: 75% peas) harvested at the milky dough stage, significantly increased the yield of forage. However, the dry matter yields of mixtures reported in this study are within range of those reported in sole cropped oat studies in New Zealand, (Howse et al., 1996; McDonald & Stephen, 1979; Yusoff, McKenzie, Moot, & Hill, 2013). Price calculations for seed show that the cost of seed for monocropped oats is $288/ha, while for the mixtures it is $319/ha, $303.5/ha, and $334.5/ha for treatments 4, 5, and 6 respectively (Agricom, 2020; Oregro-Seeds, 2020). The difference between the sole cropped oats and the most expensive mixture treatment is $46.5/ha for similar dry matter yield production.

Intercropping also improved the quality of forage. In harvest 1, all mixtures had significantly higher crude protein content and significantly lower ADF and NDF levels. The forage produced in treatment 6 at this harvest can be used to feed cows in mid-lactation based on a ME of greater than 10 MJ/kg/ha and crude protein content of greater than 10% (i.e.,15.39%) (Beef + Lamb New Zeland, 2017; Howse et al., 1996; Macdonald, Nicholas, Kidd, Penno, & Napper, 2000; McDonald & Stephen, 1979). The forage produced in treatments 4 and 5 can be used to feed growing bulls or pregnant replacement heifers, as the forage contains crude protein ranging from 13.24 to 13.88%, meeting guidelines for growing bulls (8.2-13.8%), and pregnant replacement heifers (8.2-11.4%) (National Research Council, 2000). Though there wasn't much significant difference in quality parameters at harvest 2, the forage produced from the mixtures is suitable for feeding beef cows, as it contains crude protein content that falls within the guidelines for feeding beef cows (7.9-9.1%), unlike the sole cropped oats which had crude protein content below this range (National Research Council, 2000).

Intercropping produced forage of superior quality compared to sole cropped oats. The relatively small difference in seed cost per hectare shows that farmers in New Zealand can use cereal-legume intercropping to cost-effectively improve the quality of forage.

Chapter 6 : Conclusions

a) Apart from the 25% oats: 75% peas treatment harvested at the milky dough stage; intercropping did not significantly increase forage dry matter yield.

b) Seed ratios did not significantly affect the leaf area index and the plant height of oats.

c) Intercropping improved the quality of forage only at the boot stage. Mixtures outperformed the sole cropped oats in terms of quality by having higher crude protein content and lower ADF and NDF levels. At the milky dough stage, intercropping did not significantly improve the quality of forage.

d) Intercropping did not significantly increase the metabolisable energy of forage

e) Among the mixture treatments, 25% oats: 75% peas had significantly higher crude protein and relatively lower ADF and NDF levels at the boot stage of oats.

f) The 25% oats: 75% peas mixture had the highest crude protein and metabolisable energy yield at both harvests.

g) All mixtures resulted in land equivalent ratios of greater than 1, the highest being in treatment 6 (25% oats: 75% peas), 26% more land would be required under sole cropping to produce the dry matter yield produced under intercropping in this treatment.

h) Competition ratios showed that oats were more competitive than peas.

1. Intercropping with peas can be used by farmers in the Manawatū area to improve the quality of forage oats grown for silage, the optimum seed ratio being 25% oats: 75% peas.

6.1 Recommended further research

The recommendations for further research following this study are as follows:

a) A study to assess the nutrient and nutrient transfer dynamics in the intercrop should be conducted to establish the extent of nitrogen transfer and its effect on the dry matter yield of the mixtures. The influence of lower soil fertility must also be investigated.

b) A study using other oat and pea cultivars should be conducted to determine if the current outcome is cultivar-specific.

c) Further work is required to assess the influence of planting season on yield and quality.

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Appendix 1: Mean germination percentage for oats and peas across the six treatments

Treatment	Oats	Peas
Treatment 1 (100%peas)	.	97%
Treatment 2 (100% Oats with N)	96%	.
Treatment 3 (100% Oats without N)	96%	.
Treatment 4 (50% Oats: 50% Peas)	94%	95%
Treatment 5 (75% Oats:25% Peas)	95%	94%
Treatment 6 (25 Oats: 75% Peas)	94%	93%

Both oats and peas had germination of over 90% across all 6 treatments indicating adequate seed vigour and the successful establishment of the trial (Copeland & McDonald, 1999).

Appendix 2: Seed cost calculation for each treatment

Cost of Milton oats :96 NZD/50kg (Agricom, 2020)

Cost of Secada peas: 56 NZD/40 (Oregro-Seeds, 2020)

Based on a seed rate of 150kg/ha for oats and 250kg/ha for peas, the cost breakdown for each treatment is as follows:

Treatment	Cost of oat seed (NZD/ha)	Cost of pea seed (NZD/ha)	Total cost of seed (NZD/ha)
Treatment 1 (100%peas)	$0.0	$350.0	$350.0
Treatment 2 (100% Oats with N)	$288.0	$0.0	$288.0
Treatment 3 (100% Oats without N)	$288.0	$0.0	$288.0
Treatment 4 (50% Oats: 50% Peas)	$144.0	$175.0	$319.0
Treatment 5 (75% Oats:25% Peas)	$216.0	$87.5	$303.5
Treatment 6 (25 Oats: 75% Peas)	$72.0	$262.5	$334.5