Comparison of Maize Silage and Traditional Forage Crops in New Zealand

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Abstract

Cattle wintering systems using crops including grazing kale, swede, and fodder beet crops *in situ* have resulted in soil and water quality deterioration. Nitrate leaching is the most common problem due to the high deposition of urine N driven by excess N intake. Alternative cropping systems offer a potential solution to reduce these environmental problems while maintaining or maximising productivity. We proposed maize silage as an alternative crop because it has high yield potential, flexible feeding requirements, compliments the nutritive value of pasture, and is potentially suitable for more regions in New Zealand in the future due to climate change. However, research needs to determine whether maize silage yield, feed quality and potential nitrate losses during production and utilisation means it is a viable alternative to *in situ* grazed forage crops in these areas.

Field experiments were conducted at Massey University, Tokoroa and Kiwitea to determine forage yield and feed quality, management effects and site differences in 2018/19 and 2019/20. Crop yields and forage N content were utilised to simulate urine N loads from the feeding of these forage crops. The excreted N loads were analysed in APSIM (**A**gricultural **P**roduction **S**ystems s**IM**ulator) to predict nitrate leaching losses.

Maize produced significantly higher yields compared with the winter forage crops at all Massey University trials while producing competitive yields at Tokoroa and Kiwitea. Yields ranged from 10,940 to 30,417 kg DM/ha for maize whilst wide and lower yield ranges were observed for the winter forage crops (4,579 to 22,928 kg DM/ha). Irrigation increased yields of forage crops by 29-63%. Similarly, nitrogen fertiliser increased yield by 30%, on average. The faster canopy development of maize has the advantage of intercepting more radiation in summer and suppressing weeds, contributing to greater growth and yield despite a shorter crop season.

All forage crops produced forage with good metabolisable energy content (MJ/kg DM); higher values in swede (10.1-14.5) and fodder beet (10.8-14.9) whereas intermediate values in kale (8.9-12.7) and maize (9.9-12.2). However, maize was the highest energy-yielding crop, ranging from about 200-316 GJ/ha while other crops varied from 34 to 217 GJ/ha. Protein content in kale (7.5-16.6% DM) and swede (11.4-18.2% DM) were adequate for non-lactating cows whereas maize (5.4-9.2% DM) and fodder beet (7.6-11.2% DM) were lower than recommended protein levels for dairy cows but offering an opportunity to reduce urinary N excretion. Maize also had recommended fibre content. With higher sugar contents, swede and fodder beet were poor in fibre sources, potentially prone to rumen acidosis unless considered mixed diet with high fibre feed.

APSIM modelling indicated that maize would produce the lowest urine N output while swede the highest in simulated feeding. Accordingly, N loads/ha was higher for winter forage crops especially when good yields were produced. When common feeding practices were considered, i.e., off-paddock maize feeding (no urine N deposition) and on-paddock grazing of winter forage crops (high urine N deposition), simulated nitrate losses from maize cropping systems were the lowest. Predicted nitrate losses were 21 and 32 kg N/ha for maize under irrigated and non-irrigated conditions. A ryegrass cover crop further reduced simulated nitrate losses by 20-30%. Predicted nitrate losses for fodder beet, kale, and swede crops were 126, 162, 154 kg N/ha under irrigated conditions and 72, 201, 199 kg N/ha under non-irrigated conditions, respectively in grazing systems.

keywords: APSIM, dairy, fertiliser application, fodder beet, forage brassicas, irrigation, *in situ* grazing, kale, maize silage, modelling, New Zealand, nitrate leaching, nitrogen, off-paddock feeding, simulations, swede, wintering

Dedication

This thesis is dedicated to my father, U Tin Sein who passed away in 2019 during my PhD study and my mother, Daw Than Nu, for their love, encouragement, and support in my academics since I was young.

I also dedicate this work to my wife, Sandar Tun, for her love and support in my PhD undertaking and to my son, Aung Phone Myat, my inspiration.

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Lists of Abbreviations

ADF	Acid detergent fibre
ANOVA	Analysis of Variance
AOB	Ammonia oxidising bacteria
APSIM	Agricultural Production Systems sIMulator
Asl	above sea level
BCS	Body Conditioning Score
Ca	Calcium
CP	Crude protein
CRM	Comparative Relative Maturity
DAS	Days after sowing
DM	Dry matter
DMI	Dry matter intake
DM yield	Dry matter yield
GIS	Geographic Information System
GLM	General Linear Model
HOV	Homogeneity of variance
IWG	Intensive winter grazing
K	Potassium
KL	Kiwitea late trial
LAI	Leaf area index
LSD	Least significant difference
LS means	Least square means
LTM	Long term mean
LUMASS	Land-use Management Support System
ME	Metabolisable energy
MU	Massey University
MUI	Massey University Irrigated trial
MUL	Massey University Late trial
MUNI	Massey University Non-Irrigated trial
N	Nitrogen
Na	Sodium

NDF	Neutral detergent fibre
NIRS	Near-infrared spectroscopy
NIWA	National Institute of Water and Atmospheric Research
NO_3-N	Nitrate nitrogen
NRC	National Research Council
NSC	Non-structural carbohydrate
NZ	New Zealand
P	Phosphorus
R^2	coefficient of determination
RCB	Randomise complete block (design)
SMCO	S-methyl cysteine sulphoxide
SSS	Soluble sugars and starch
T_b	Base temperature
TDR	Time Domain Reflectometry
T_{max}	Maximum temperature
T_{min}	Minimum temperature
TT	Thermal time
US	United States
VFA	Volatile fatty acids
WFC	Winter forage crops (fodder beet, kale, and swede in this manuscript)
WSC	Water Soluble Carbohydrate
WU	Water use
WUE	Water use efficiency

Units and Terms

°C	Celsius
°Cd or °C/day	Celsius per day
°Cd/leaf	degree days per leaf
c/kg DM	cents per kilogram dry matter
c/MJME	cents per Mega Joule of metabolisable energy
g N/cow/day	grams nitrogen per cow per day
GJ/ha	Giga Joule per hectare
ha	Hectare
kg DM	kilogram of dry matter
kg DM/ha	kilogram of dry matter per hectare
kg/ha	kilogram per hectare
kg N/ha	kilogram of nitrogen per hectare
l/ha	litre per hectare
M	meter (s)
Mm	millimetre (s)
m^2	meter, square
mg/kg	milligram per kilogram
mg/L	milligram per litre
MJ/day	Mega Joule per day
MJ/kg DM	Mega Joule per kilogram of dry matter
MJ/m^2	Mega Joule per square-meter
$MJ/m^2/day$	Mega Joule per square-meter per day
$plant/m^2$	Plants per square-meter (plant density)
plant/ha	Plants per hectare (plant density)
%	percentage
% DM	percent dry matter
t/ha	tonnes per hectare
t DM	tonnes of dry matter
t DM/ha	tonnes of dry matter per hectare

Terminology

Forage brassicas

Forage brassicas crops refer to kale and swede crops in this manuscript.

Winter forage crops

Traditional forage crops or winter forage crops (WFC) refer to kale, swede, and fodder beet in this manuscript.

Forage crops growing practices

Forage crops can be located on the dairy farm (milking platform), on a separate farm manged by the dairy farmer (support block) or on a farm owned by another farmer (grazier) (Edwards et al., 2017).

Intensive winter grazing (IWG)

Intensive winter grazing means the grazing of livestock on an annual forage crop at any time in the period that begins on 1 May and ends with the close of 30 September of the same year (New Zealand Government, 2022).

Intensive wintering

Intensive wintering is defined as, "*a farming practice where livestock (cattle, sheep, deer) are confined over winter to outdoor feeding areas planted with annual forage crops (e.g. swedes, kale and fodder beet)*" (Ministry for the Environment and Ministry for the Primary Industries, 2021).

Chapter 1 Introduction

1.1 General introduction

New Zealand (NZ) is the world's largest exporter of dairy products (Ma et al., 2019) and produces 3% of global milk production (DairyNZ, 2020). Dairy farming contributed 34% of the total export value in 2019-20 ($19.7 billion) and employed 50,000 people (DairyNZ, 2020; LIC and DairyNZ, 2021). In the livestock sector, dairy cow numbers increased 78% from 1992 to 2021 whereas the numbers of sheep, beef and deer decreased 51%, 15%, and 28% respectively (Table 1.1). The increase in cow numbers was primarily due to the conversion of sheep and beef farms to dairy. The conversion of forest land to dairy has also contributed (MacLeod & Moller, 2006; Quinn et al., 2009).

Table 1.1. Comparison of livestock numbers (thousands) highlighting the intensification of dairy farms between 1992 and 2021 in New Zealand (Statistics NZ, 2021).

Year	Sheep	Beef	Dairy	Deer
1992	52,568	4,676	3,468	1,135
2002	39,572	4,491	5,162	1,648
2012	31,263	3,734	6,446	1,061
2021	25,733	3,965	6,185	814
% Change over time 1992 – 2021	**-51%**	**-15%**	**+78%**	**-28%**

There are currently around 4.92 million milking cows of the total 6.18 million on the effective land area of 1.7 million hectares (DairyNZ, 2020; Statistics NZ, 2021). Of the total cows, about 58% are in the North Island with 42% in the South Island (Figure 1.1) (LIC and DairyNZ, 2021). There was a noticeable increase in cow numbers in the South Island during the last decade (2010/11 to 2020/21), particularly in Canterbury, Southland, and Otago regions (Figure 1.1). This was due to the conversion of a large number of sheep and beef farms to dairy with the availability of irrigation (Drewry et al., 2021; PCE, 2015) and the greater profit with high value of dairy commodities in the world markets (PCE, 2004; Quinn et al., 2009).

New Zealand's pastoral farming system is mainly based on the perennial ryegrass-white clover pastures (Chapman et al., 2017; Waghorn & Clark, 2004) with supplementary feeding from home-grown feed in summer or winter periods (Pinxterhuis et al., 2015). The pasture-based system allows the dairy sector to be competitive in international markets with its low-cost production. However, the intensification of dairy farming with increasing cow numbers means the industry will require more feed supply in the future (Ministry for Primary Industries, 2017). In a temperate dairy farming system, a feed shortage often occurs in summer due to moisture stress, and during winter periods when the pasture growth is restricted by low temperatures. This can result in a feed gap and a drop in milk production. Unlike Europe, where imported supplement feed is often used, NZ farmers usually use home-grown supplementary feed crops to feed the animals at the time of a feed shortage (Pinxterhuis et al., 2015). Consequently, annual forage crops play a significant role in providing supplementary.

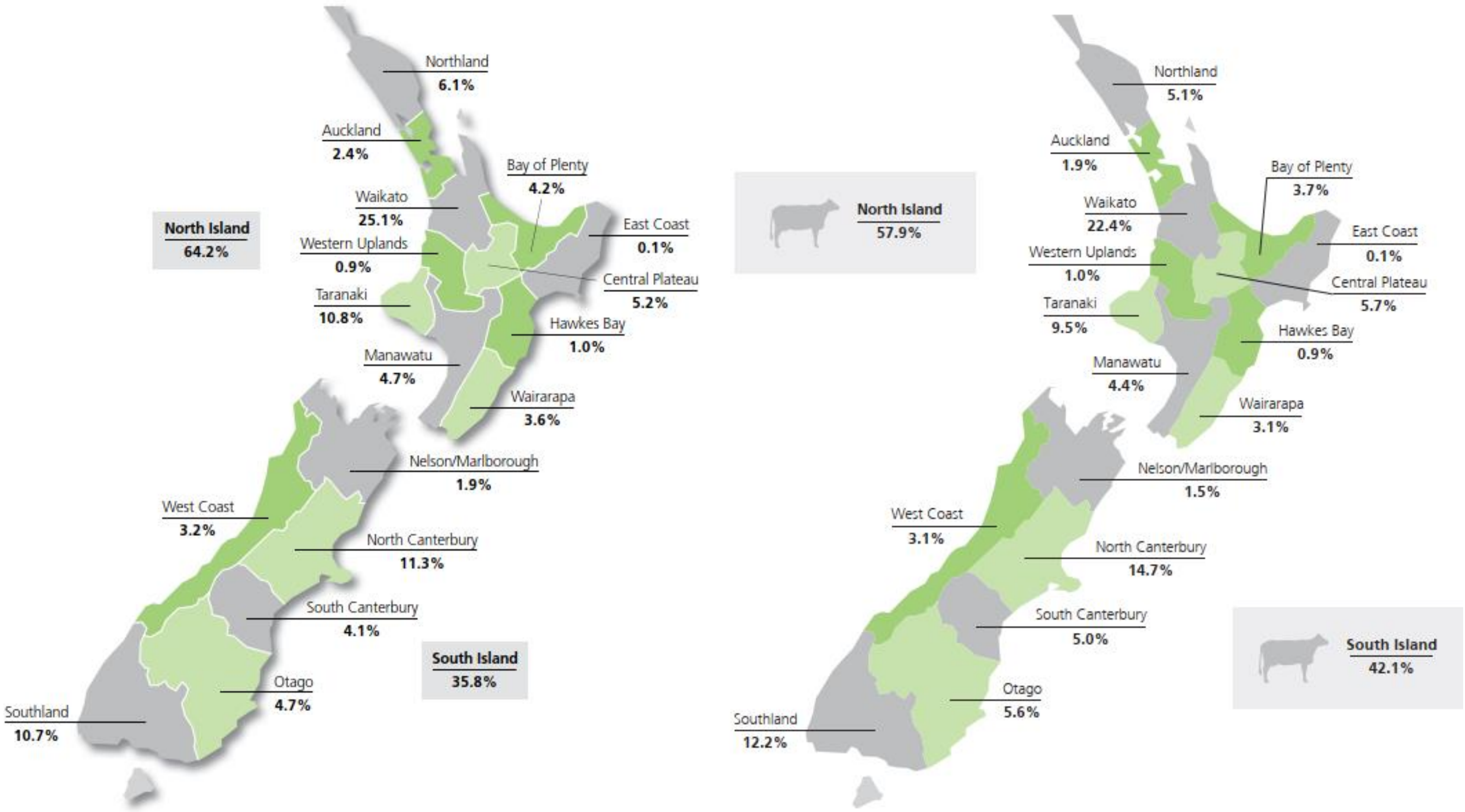


Figure 1.1. Regional distribution of dairy cows (percentage of total herd) in New Zealand in 2010/11 and 2020/21 (LIC and DairyNZ, 2011, 2021).

Several annual forage species such as cereals, legumes, herbs, plantain, beets, and forage brassicas are available for annual cropping in NZ (Havilah, 2011; Westwood, 2021). Among them, kale, swede, fodder beet, maize, turnip, oats, and triticale are well suited to NZ farming systems (de Ruiter et al., 2009a; Minnée et al., 2009; Wilson et al., 2006). These forage crops may be managed as a sole production system or mixed with annual or perennial pastures to provide a better feed supply or manage risks over a year when feed deficits occur. The annual forages may be directly grazed *in situ* or mechanically harvested and fed fresh off-paddocks or conserved as silage for later use (Westwood, 2021).

Some forage crops, like forage brassicas, are associated with intensive grazing, particularly in wet winter periods resulting in significant loss of nutrients to waterways. This results in the deterioration of soil and water quality. The grazed paddocks are often affected by treading damage from grazing animals, pugging soil (Chamen et al., 2015; Drewry et al., 2021; Yi et al., 2022), and hence, require a recovery time to let the soil dry after grazing (3-5 months fallow) to establish a new crop (Malcolm et al., 2019). During the fallow periods, nutrient leaching from grazed paddocks is common due to lack of cover crops. If the grazed paddocks are close to the critical areas near waterways, surface runoff loss of phosphorus (P) is also a major concern in forage grazing systems. Nitrogen leaching losses can contaminate water bodies, resulting in nitrate levels that exceed the required standard for drinking water (11.3 mg/L) (Ministry of Health, 2005). In addition, winter grazing systems may influence animal health and welfare through for example, ruminal acidosis (Fleming et al., 2021b) or having to bed in muddy soil (Dalley et al., 2022).

Animal urine is the primary cause of nitrogen leaching losses from farming activities, associated with excess N intake (Cichota et al., 2010b; Dijkstra et al., 2013; Ledgard et al., 2000). Research has highlighted the management of the composition of feed is a potential solution to reduce the urine N excretion (Dalley et al., 2017; de Ruiter et al., 2019). It is important to note that pasture in NZ is typically high in protein, so supplementary feed crops should ideally be low protein.

Management strategies have been proposed to reduce N leaching losses including soil, plant, N fertiliser use, herd selection, dairy farm effluent (FDE) management, controlled or restricted grazing management options necessary to improve the efficiency of resource use (Christensen et al., 2010; Christensen et al., 2019; Garcia et al., 2008; Monaghan et al., 2017; Pinxterhuis & Edwards, 2018; Pinxterhuis et al., 2015). However, the opportunity to reduce N losses via excreted urine from farm animals is still limited under grazed *in situ* cropping systems with kale, swede, and fodder beet.

This issue is based on the cropping choice required by the system to fill in the feed gap in summer or winter, as pasture quality or quantity declines. Although there is no single best approach, an alternative cropping option is one of the potential solutions to overcome a complex system-wide issue associated with winter forage crops. We proposed maize silage as an alternative cropping option to winter forage crops with potentially complement in nutritive values to the pasture-based system as well as adaptive to a future warmer climate. At the same time, it is important that maize silage should have competitive yield and forage qualities compared with these winter forage crops in different environments in NZ. Therefore, this PhD project will highlight the assessment of dry matter yield, forage quality and nitrate leaching losses of maize silage and winter forage crops.

1.2 Research aim

The research aims to improve the annual feed supply with particular emphasis on the opportunity of maize silage combined with an Italian ryegrass crop in the cropping system compared with winter forage crops (kale, swede, and fodder beet). In addition, the research also aims to quantify N leaching losses from different forage crops via a modelling study.

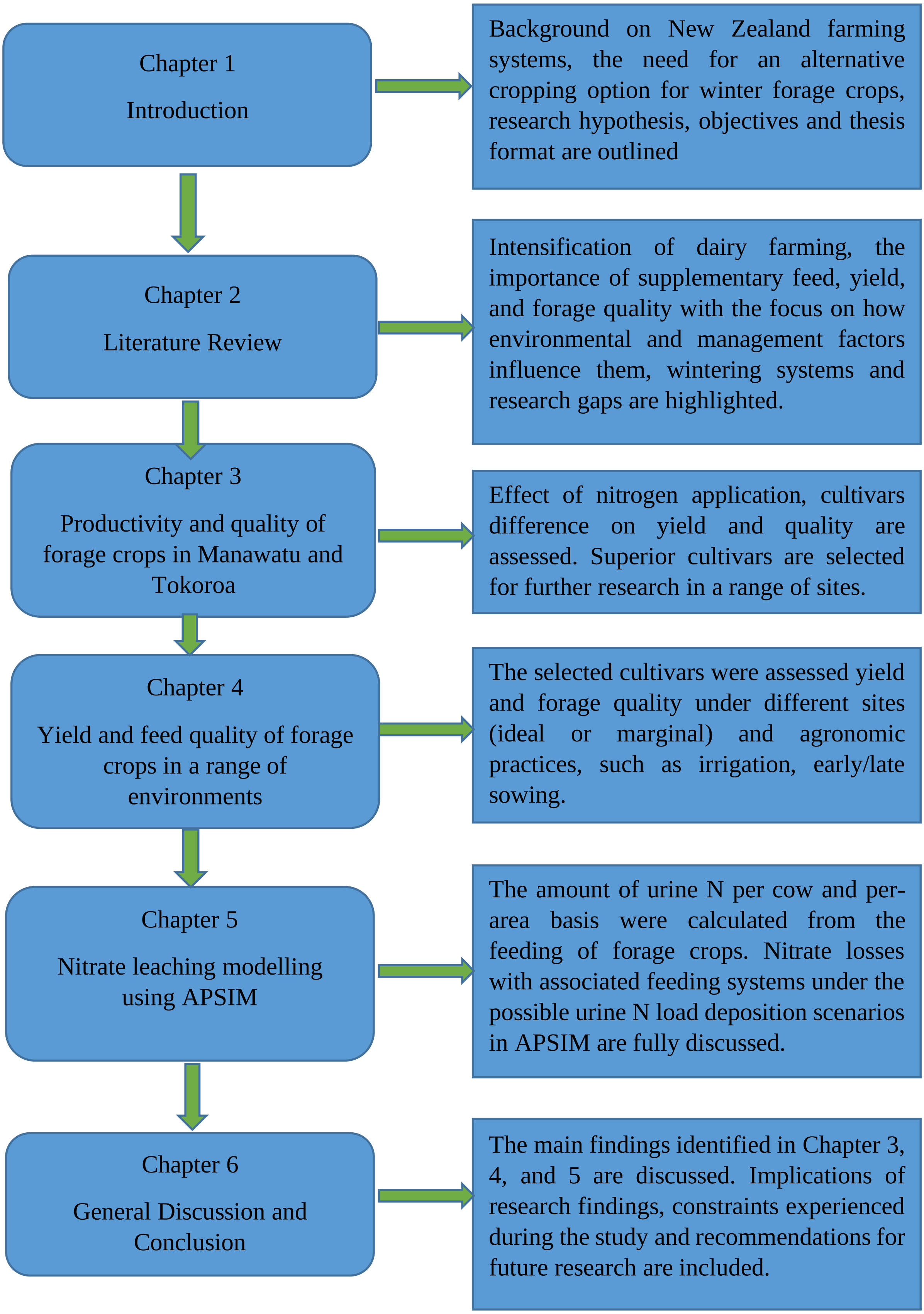
1.3 Research hypothesis

Maize silage (*Zea mays* L.) offers a viable alternative to winter forage crops such as swedes (*Brassica napus* var. *napobrassica*), kale (*Brassica oleracea* var. *acephala*) and fodder beet (*Beta vulgaris* L.) grazed *in situ*.

1.4 Specific objectives

1. to quantify total dry matter (DM) yield and nutritive values of different forage cropping options in a range of environments in NZ
2. to investigate the growth and development of maize silage and traditional winter forage crops
3. to identify site and forage species interactions for yield and forage quality
4. to assess potential nitrate leaching losses resulting from grazing different forage crops

1.5 Thesis format



Chapter 2 Literature Review

2.1 Introduction

This review explores the nature of farming systems in New Zealand (NZ), the importance of supplementary feed crops, particularly in the dairy industry, and provides a brief overview of selected forage crops used in this study. It also includes the influence of climatic factors and management factors on the yield and feed quality of forage crops. The environmental impacts resulting from winter grazing of forage crops, particularly nitrate leaching, and alternative cropping options able to minimise these environmental impacts, are outlined. To estimate nitrate leaching losses, modelling platforms are briefly discussed, and justification is made in choosing an APSIM model in this research. Finally, the knowledge gap is addressed, comparing forage crops under different management in a range of environments in NZ.

2.2 Intensification of dairy farming

Historically, pastoral agriculture was established with the settlement of Europeans in the 1840s (MacLeod & Moller, 2006; Quinn et al., 2009) and at that time was particularly reliant on permanent pastures of grasses and natural vegetation. Thereafter, the farming industry developed rapidly with the development of refrigeration in 1882 and traditional farming slowly evolved to improved pasture management around 1920 (Quinn et al., 2009). Today NZ's agriculture could be considered as pasture-based livestock production but using industrial systems. Although perennial ryegrass/white clover based pasture remains the most important forage used in NZ, pastoral farmers often use forage crops to meet seasonal feed deficits (Basset-Mens et al., 2009).

Intensive farming is a characteristic of the dairy sector. MacLeod and Moller (2006) reported that there was a strong and steady intensification of agriculture between 1960 and 2001. During this period, some sectors declined, particularly sheep farming. The reduction in sheep farming and rapid conversion to dairy farms occurred as a result of the removal of farm subsidies in the mid-1980s (MacLeod & Moller, 2006), and the relative profitability of dairy compared with sheep and arable farms (Millner & Roskruge, 2013). Although the numbers of beef cattle were higher than dairy cows in 2002, by 2020 the population of dairy cattle (6,185,000) was about double that of beef cattle (3,883,000) (Statistics NZ, 2021).

The expansion of dairy farms is more obvious in the South Island, especially in Canterbury and Southland (Wales & Kolver, 2017). For example, dairy cows numbers increased dramatically from 450,000 to 700,000 cows in Canterbury from 1994 to 2009 due to the conversion from sheep and mixed cropping farms (sheep numbers declined from 9.7 to 5.5 million) (Dynes et al., 2010a). Quinn et al. (2009) stated that 515,000 hectares of sheep/beef farms were converted to dairy farms from 1990 to 2007 in NZ. Likewise, Pangborn and Woodford (2011) mentioned the land used for dairying increased from 20,000 to 190,000 ha in Canterbury alone between 1980 and 2009. Subsequently, this intensification of dairying has also brought the increased use of irrigation systems (Birendra et al., 2018; Drewry et al., 2021) with the opportunity to produce more pasture but also to adapt more forage cropping options. Intensification of dairy farming is widespread in these regions, e.g. Canterbury now has over half (60.5%) of NZ's total irrigated land area (Dark, 2020; Dynes et al., 2010a).

Intensification is also associated with increased stocking rates and productivity. For example, between 1997 and 2017, the average stocking rate increased from 2.42 to 2.81 cow/ha and milk solid production increased from 301 to 381 kg MS/cow (Clark, 2011;

LIC and DairyNZ, 2017). The Ministry for Primary Industries expected dairy cow numbers to grow about 1.5-2.0% in 2016. These high stocking densities resulted in increased use of supplementary feed crops over the winter due to low temperatures and consequently pasture growth because they offer low-cost yet high-quality forage (Chakwizira et al., 2014c; Chakwizira et al., 2010; Wilson et al., 2006).

Another driver of increased production of supplementary feeds is the cropping strategy. To maximise the yield and quality of crop production farmers often utilise year-round crop sequences rather than rely on a single crop (Chakwizira et al., 2017b) increasing the area of supplementary feed crops. de Ruiter et al. (2009a) highlighted that a higher proportion of supplementary feed crops on farms was an option to increase feed production in NZ. Increased use of supplementary feeds was suggested for the dairy industry (Clark et al., 2001; Minnée et al., 2009); researchers set a goal of 45 t DM/ha annually from supplementary feed crops (Beare et al., 2010). In that context, forage crops, like kale, fodder beet, maize, turnip, oats, and triticale are well suited to supply feed during the winter period when pasture growth is poor (de Ruiter et al., 2009a; Minnée et al., 2009; Wilson et al., 2006). These crops play a major role in NZ farming in terms of sustainable milk production, providing winter feed (Malcolm et al., 2016b; White et al., 1999) and as a part of a rotational system (Teixeira et al., 2012). These crops are also important as a break crop during pasture renewal as well as diseases and pest control in cropping systems.

Along with the intensification of agricultural production after the 1960s and farmers' awareness of the production limits resulting from feed shortages when solely relying on permanent pasture, most dairy farmers have subsequently depended on supplementary feed crops, off-farm grazing and imported silage to support high stocking rates and greater milk production per hectare (MacLeod & Moller, 2006; Pinxterhuis et al., 2015). Consequently, these intensifications in farming and the shortage of feed during drought and winter periods primarily demand the increased use of home-grown supplementary feed crops.

2.3 Supplementary feed crops in NZ

NZ farming is characterised by “intensive and flexible multi-crop rotations”, so dairy farms mostly use a pasture-based cropping system with the addition of supplementary feed crops to improve the farm productivity and milk yield per cow. The major supplementary feeds are maize, forage cereals (triticale, oats, barley), herbs (chicory, plantain), forage brassicas (kale, swede, turnip, rape), legumes (lucerne, clover) and fodder beet. The general overview of the sown area of these crops is given in Table 2.1.

After pasture (including hay and silage), lucerne, forage brassicas, fodder beet and maize silage are the most important supplementary feed crops in NZ. Maize silage is widely grown in the North Island (90%), mostly in the Waikato regions. In contrast, approximately 74% of the area sown with forage brassicas was in the South Island (Table 2.1). Of the total forage brassicas harvested, 31% were grown in the Canterbury region with 7% each in the Manawatu and Waikato regions (Statistics NZ, 2012, 2017). At present, kale, swede and turnip combined accounted for 236,677 ha in 2017 (Statistics NZ, 2017). Kale and swede contributed 42% of the total forage brassica crop production (Chakwizira et al., 2012; White et al., 1999), and were mainly grown in the South Island (Malcolm et al., 2016a).

For this project, maize silage, fodder beet and brassica (kale and swede) were chosen to compare yield and feed quality as well as to investigate the impact of these crops on the environment.

Table 2.1. Area (ha) of supplementary feed crops in New Zealand in 2017 (Statistics NZ, 2017).

No.	Type	North Island	South Island	Total
1.	Pasture/lucerne (hay, silage and baleage)	369,498	432,384	801,882
2.	Maize silage	37,174	4,094	41,268
3.	Maize green feed	6,899	4,335	11,234
4.	Cereal, silage or cereal baleage	3,386	22,128	25,514
5.	Other crops silage	7,991	9,824	17,815
6.	Lucerne	10,105	40,611	50,716
7.	Forage brassicas (swede, turnips, kale)	62,616	174,061	236,677
8.	Other supplementary feed crops	33,523	34,053	67,576
9.	Fodder beet	-	-	60,000ꜜ

ꜜ total estimated area in previous reports from 2016 to 2018 (Chakwizira et al., 2016a; Ministry for Primary Industries, 2020a)

2.3.1 Maize silage

Maize silage is also called fodder maize because it is harvested when the plant is still green and the cob is at an immature stage (Boller et al., 2010). Maize has become one of the most important crops in NZ’s pastoral farming sector over the last few decades. Farmers grow maize silage crops as supplementary or complementary feed for livestock to meet seasonal feed deficits (Tsimba et al., 2014), particularly in the North Island as part of the pastoral rotation system (Densley et al., 2006). One possible reason is that maize cropping can maximize the herbage yield of sequential or rotational cropping (Chakwizira et al., 2017b) and keep farm production levels high with good reproductive performances from herds (Williams, 2012). More specifically, a mixture of silage maize and other forage crops can create opportunities for greater feed intake, which produces greater milk yield and 15% more total dry matter yield, than a typical pasture system (Williams, 2012).

In addition to the yield advantage of maize inclusion in cropping systems, climatic conditions also favour the growth of maize in most parts of the country currently and possibly in the future. Warmer weather favours maize growth in different regions of the country and results, for example, in increased yields and silage quality in southern regions, due to a long growing season (Teixeira et al., 2012). This favourable warm weather will be likely to continue to favour the growth of maize crops in marginal areas of the country in the future climate scenarios as well. Moreover, being a C_4 plant type, maize has efficient CO_2 use and typically photosynthesizes more than C_3 types in full sunlight (Kerr, 1975), so is well suited to the warmer regions of NZ (Kerr, 1975; Wilson et al., 1994).

Maize silage is widely grown in the North Island because the climate favours its growth more than in the South Island (Chakwizira et al., 2017b; Densley et al., 2006). The main maize growing regions in NZ are Canterbury, Hawkes Bay, Taranaki, Waikato, Bay of Plenty, Manawatu, and Northland. According to agricultural production statistics, the total harvested area of maize silage was 41,268 ha in 2017 (Table 2.1). The respective harvested maize silage areas for the North and South Islands are approximately 90% and 10% respectively (Statistics NZ, 2017). Arable Industry Marketing Initiative (2021) survey stated that maize silage area increased from 43,087 ha in 2011 to 55,241 ha in 2021 with a peak of 60,110 in 2020 during the last decade.

In contrast to the North Island, less maize is planted in the South Island. It is partly because of insufficient thermal time to allow crop maturity with an increased risk of frost during initial crop establishment (Millner & Roskruge, 2013) or just before silage harvest maturity (Wilson et al., 1994). The climatic risk due to a shorter potential growing season means that short-season maize hybrids (CRM = 75-85) are suitable for the Canterbury region whereas a wider maturity maize hybrid range (CRM = 90-115) is possible in the

North Island regions due to greater temperatures between August and February (Fletcher et al., 2011; Tsimba et al., 2013b). Under warmer climate conditions, farmers sow silage maize as early as possible, with maximum yield obtained from the early to mid-October sowing (Densley et al., 2005; Tsimba et al., 2013b). Maize is generally followed by winter forage crops planted in autumn, such as grasses, legumes, and cereals (Chakwizira et al., 2017b).

2.3.2 Cover crop after maize

Minnée et al. (2009) defined a cropping sequence as "the practice of growing a sequence of different crops in the same area in successive seasons". The inclusion of crop species has the potential to increase annual forage yield because the efficiency of resource use depends on the crop performance/types. Furthermore, growing forage crops after permanent pasture can complement nutritive values at critical supply times (Garcia et al., 2008). Sequential cropping utilises nutrients more efficiently, so often produces a higher production per unit area over a given time than sole crop or mono-cropping.

A crop or perennial pasture can be planted after maize if harvested early in autumn. This research also aims to quantify the whole sequence yield of maize and a cover crop to find opportunities for maize to increase annual feed supply in the cropping systems. Maize silage is particularly suited to the double cropping system because harvesting occurs before the plant reaches physiological maturity (Kerr, 1975). After maize, there is a time to grow short-term grasses or cereal species on maize plots in early autumn. As a sequential crop, this additional crop can contribute to a greater total DM production per unit area compared with the total yield of winter forage crops within the same crop duration.

2.3.2.1 Italian ryegrass as a second crop after maize

The second crop after maize is an important consideration as the farmer aims to optimize DM yield. Chakwizira et al. (2017b) suggested that the most suitable rotational crops with maize in an NZ context were oats, triticale, and Italian ryegrass. These three crops can give high biomass yields and acceptable ME quality. The highest DM yield was obtained from oats and Italian ryegrass: about 10.5 t DM/ha with early sown maize (Chakwizira et al., 2017b). A crop of oats and ryegrass after a mid-April maize harvest in Palmerston North yielded 10 t DM/ha and 6 t DM/ha, respectively (Kerr, 1975). In addition, these potential crops have high crude protein: 17.4% in triticale; 26.4% in oats; and 28.2% in Italian ryegrass (Macdonald et al., 2012). This means they can supplement the required protein value provided by maize crops in the feed diet.

In choosing a winter crop after maize, Chakwizira et al. (2017b) suggested Italian ryegrass with the earlier harvest of maize silage crops whereas oats or triticale with the later harvest. Moreover, they also reported that Italian ryegrass had 1 MJ ME/kg DM higher energy content than cereals. Italian ryegrass produces high winter forage yields due to rapid establishment, early spring growth and a good response to N fertiliser (Hunt, 1962). Italian ryegrass is widely grown in rotation with maize silage crops in NZ (Densley et al., 2006; Macdonald et al., 2012). Additionally, in Northern Italy whole crop maize silage and Italian ryegrass showed good performance on environmental impacts expressed per unit of net energy for lactation (Zucali et al., 2018). Trindade et al. (2009) also found that early sown Italian ryegrass could pick up most of the soil NO_3-N accumulated in the 30-cm soil layer after maize harvest. As this research is not only designed to optimize DM yield but also to maximise energy yield and minimise nitrate levels in the soil, Italian ryegrass was chosen as a second crop after the maize harvest.

2.3.3 Fodder beet

Fodder beet is a subspecies of *Beta vulgaris* L., a member of the Chenopodiaceae family, and is related to mangel and sugar beet (Clark et al., 1987; Lange et al., 1999; Matthew et al., 2011). Fodder beet crops have been grown in NZ for a century but use was limited due to the perception of toxicity, in particular the presence of oxalic acid (Gibbs et al., 2015). However, the sown area of fodder beet has recently increased, reaching about 15,000 ha in 2014 (Gibbs, 2014; Malcolm et al., 2016a) and about 45,000 to 60,000 ha in 2015-16 (Chakwizira et al., 2016a; Stocker et al., 2016). In comparison, only about 100 ha was planted in 2006 (Gibbs, 2014; Malcolm et al., 2016a). The increased area planted in fodder beet is due to high yields, high energy content and low nitrate poisoning risk (Chakwizira et al., 2016a; Khaembah et al., 2017; Matthew et al., 2011), as well as a longer window of use, reduced land requirement compared to other winter crops (Gibbs, 2014) and its versatility (Gibbs et al., 2015).

The potential yield of fodder beet is high. Mean yields of 14-29 t DM/ha have been reported (Chakwizira et al., 2018) with the highest recorded yield in NZ being 35 t DM/ha (Matthew et al., 2011). At final harvest, the root contributes more than 80% of total DM (Chakwizira et al., 2014a; Chakwizira et al., 2018) and included more than 60% sugars, approximately 10% crude protein (CP) and 12% neutral detergent fibre (NDF) content (Matthew et al., 2011). However protein content can vary; Chakwizira et al. (2014a) achieved a protein content of 7% in fodder beet while Clark et al. (1987) noted fodder beet was a poor source of protein.

Fodder beets used in this research are monogerm seeds because monogerm cultivars are better in establishment and yields (Milne et al., 2014; Westwood, 2021). Monogerm seeds are genetically selected, so one plant per seed can produce uniform shaped and larger bulbs (Westwood, 2021). Fodder beets are sown in spring when the soil temperature is 10°C and above. They are established at 80000-90000 plants/ha in general but also ranged the population to 80000, 100000, and 110000 plants/ha with a drilled row spacing of 30, 40 and 50 cm apart (Chakwizira et al., 2016b; Westwood, 2021). Fodder beets are relatively anchored in the soil than mangel beets or sugar beets, with about 40-50% of bulbs above the ground, so less effective in grazing compared with mangels (Westwood, 2021).

There is also concern about potential animal health issues when grazing fodder beet. Fodder beets can potentially risk subacute and acute ruminal acidosis in ruminants (Fleming et al., 2021b; Pacheco et al., 2020; Waghorn et al., 2018) because of the high water-soluble carbohydrate (principally sucrose) content of bulbs (Fleming et al., 2021a; Fleming et al., 2020b). For example, acidosis developed in 25% of cows offered 40% of daily intake as fodder beet (Fleming et al., 2020b). Therefore, mismanagement of fodder beet feeding can cause fatalities in ruminants.

2.3.4 Forage brassicas

Forage brassicas are generally biennials, with the first season being vegetative growth accumulating food reserves used to help produce seed in the second season (de Ruiter et al., 2009b; White et al., 1999). They are widely used as supplementary feed for livestock in Australia and NZ (Fletcher et al., 2012; Wilson et al., 2006). Forage brassicas are mainly grown in the cooler areas of the South Island, and in the dry east coast and central North Island regions (Chakwizira et al., 2010). Forage brassica crops have a potentially high yield with good quality forage (Wilson et al., 2006), generally producing about 5-18 t DM/ha (White et al., 1999). Moreover, they can be used as a break crop for pasture renewal (Wilson et al., 2006). Brassicas, such as mustard, are also used as a substitute for legumes and grasses in terms of green manure, and can significantly increase soil organic carbon and soil porosity (Collins et al., 2007). Among the forage brassicas, kale and swede were chosen for this research, due to their high production volume, about 42% of total forage brassicas in NZ (White et al., 1999). In addition, kale and swede provide feed available during the winter periods when feed deficits often occur in winter in the pastoral systems.

2.3.4.1 Kale

Kale (*Brassica oleracea* var. *acephala* L.), previously called chou moellier or chou, is represented by three types in NZ: short marrow-stem, intermediate, and giant (tall) types (Westwood et al., 2014). The giant kale has more yield potential compared with intermediate and short types probably due to the plant stature with a bigger stem (Westwood, 2021) but high stem yields would affect its utilisation.

Kale is normally planted from September to early October for summer use and mid-November to late December for winter use (White et al., 1999). However, winter grazing of kale is mainly used for dairy cows (Fletcher et al., 2012) while summer feeding is usually for sheep and beef cattle (Chakwizira et al., 2014c). Kale is sown at 15 cm row spacing with a seed rate of 3-4 kg/ha (Minnée et al., 2009; White et al., 1999) and provides a single crop for grazing during winter. The average growth rate of a kale crop is 150 kg/ha/day, and the peak mid-season growth average is 250 kg/ha/day (Wilson et al., 2006). Yields of kale crops in NZ range from 9 to 18 t DM/ha (Chakwizira et al., 2009; Chakwizira et al., 2011a; Chakwizira et al., 2012; Chakwizira et al., 2010). de Ruiter et al. (2009a) reported that kale sown in October gave a high biomass yield (about 21.3 t DM/ha) in Canterbury. Kale can be harvested or grazed at 170-220 DAS, but earlier grazing may result in lower yields (Westwood et al., 2014).

Kale has a higher level of SMCO (S-methyl cysteine sulphoxide), a non-protein amino acid, than either swede or turnip (Fletcher et al., 2010b; White et al., 1999). Short stem kale is not recommended for stock feed because of its potentially elevated toxicity risk to cows due to an elevated level of SMCO, higher levels of glucosinolates, and nitrate (White et al., 1999) although toxicity is caused by a number of factors such as timing of N or S fertiliser application or feeding of flowering plants. Thus, the short stem kale was not chosen for this research. Cows grazing on forage brassica crops (especially with a higher content of SMCO) may have 'red water' (also known as haemolytic anaemia/haemoglobinuria or kale anaemia). The symptoms of 'red water' includes pink or dark red urine, weakness, diarrhoea, increased heart rate, decreased appetite, and consequently result in loss of body condition and liveweight in cows (Nichol et al., 2003).

2.3.4.2 Swede

Swede (*Brassica napus spp. napobrassica*) is a root crop and has a neck at the crown portion (whereas turnip has no neck). Swede is generally planted using a conventional or ridge system from mid-November to late December in NZ. The seed rate is 0.75-1.0 kg/ha for 15 cm rows in a conventional system and 0.5-0.7 kg/ha for 60 cm ridged rows (White et al., 1999). The ridge system is good for reducing seed rates as well as controlling weeds and drainage. However, the seed placed at the top of the ridge is likely to dry out and consequently have poor germination, especially in dry areas (<800 mm rainfall) (de Ruiter et al., 2009b). Therefore, the current research used the drill seeding rather than the ridge system.

Swede is used for both cattle and sheep grazing in winter (Fletcher et al., 2012). Yields of 11.4 to 15.2 t DM/ha were reported by Chakwizira et al. (2012), compared with 9 to 18 t DM/ha (Chakwizira et al., 2011a; White et al., 1999) and 15 to 20 t DM/ha in

Southland (de Ruiter et al., 2009a; Gowers et al., 2006). Swede is normally grown at the same time as kale and is ready to graze about 170-220 DAS (in late May to August).

Like kale, swede also has a potential adverse effect of high glucosinolate concentration on animal health. Dairy farmers encountered cow illness and death in grazing in the Southland and Otago. It was shown that the high concentration of glucosinolates, “progoitrin” in leaf and flowers (reproductive stage) can cause toxicity and liver damage in cattle (Dalley & Petch, 2016; Dalley et al., 2015; Westwood, 2021). At flowering, water-soluble carbohydrates from swede bulbs also translocate to the reproductive parts, so less palatability of bulbs and reduced utilisation if grazed in the late season (Westwood, 2021). Swede is also susceptible to club root and dry rot diseases, hence used it for a first year cropping season rather than as a second crop after any other forage brassica crop (DairyNZ, 2010).

2.4 Dry matter yield and yield parameters of forage crops

2.4.1 Dry matter yields of forage crops

Dry matter yield is one of the most important factors in crop production since it is the first compared to decide whether the crop is economically profitable or not in terms of crop production per unit area. From sections 2.3.1 to 2.3.4 the potential yield ranges of forage crops in NZ are outlined. Compared to the average annual pasture yield of ~15-17 t DM/ha (Macdonald et al., 2012), the cultivation of supplementary forage crops is appealing to farmers due to their yield potential as well as feed supply during feed deficits. The average yield of chosen crops is noted as ~22 t DM/ha in maize (Densley et al., 2006; Shaw et al., 2009; Williams, 2012), 5-18 t DM/ha in brassicas (White et al., 1999), ~20 t DM/ha in fodder beet (Chakwizira et al., 2018; Matthew et al., 2011).

Dry matter yields varied substantially with plant species and their yield components under the given soil fertility, environmental factors, and management practices. The previous studies reported that DM yield and nutritive values significantly vary with cultivar choice (Millner, 2002; Millner et al., 2005; Westwood et al., 2014), fertiliser application (N, P fertilisers) (Chakwizira et al., 2014a; Chakwizira et al., 2009; Chakwizira et al., 2011a; Wilson et al., 2006), and irrigation management (Chakwizira et al., 2016a; Gallo et al., 2014; George et al., 2013).

The comparison between forage crops quantified for DM yield alone would not be enough since crop yield components, the response of these components to treatments, crop growth and development patterns are varied with plant species. Depending on forage species, yield components may differ in their contribution to total DM yield. For maize silage, yield components are grain, cob, leaf, and stem being used for fodder. The yield contributing parts are leaf and stem in kale while leaf and bulbs for swede and fodder beet. The relative proportion of these plant parts may influence the total yield and feed quality. Together with quantifying DM yield, it is necessary to highlight how the treatments and environmental factors influence the growth and development of these plant parts as well as their association with total yield and feed quality in this study.

2.4.2 Morphological components

Fodder maize yield components were mainly divided into grain and stover or all four components such as leaf, stem, cob, and grain. Previous research in Palmerston North showed that different components of maize hybrids, such as leaf, stem, cob, and grain were significantly different in their contribution to the yield and ME content of maize hybrids (Millner et al., 2005). Millner et al. (2005) also found that grain contributed the most at approximately 41.2-50.7% of biomass yield from maize hybrids. Again, the harvest index (grain to grain + stover ratio) varied from 36% to 57% of maize hybrids due to the environments and moisture conditions in previous research (Havilah, 2011; Tsimba, 2011).

In contrast to maize, winter forage crops comprised leaf and stem/bulb as yield contributing components. Approximately 60% of total DM yield was from the stem in kale crops (de Ruiter et al., 2009b; Wilson et al., 2004) but >70% in giant kale, affecting feed quality (Westwood et al., 2014; Westwood & Mulcock, 2012). Again, the proportion of bulb (~70%) was highly significant to the total DM yield in swede cultivars (Chakwizira et al., 2011a; de Ruiter et al., 2009b; Gowers et al., 2006). Likewise, about 80% of total DM yield comes from the bulbs in fodder beet (Chakwizira et al., 2014a; Matthew et al., 2011; Milne et al., 2014).

2.4.3 Leaf development

The types of crops chosen in this research vary in yield contributing parts: leaf, stem, cob, and grain in maize silage; stem and leaf in kale crop; leaf and bulb in swede and fodder beet crops. Therefore, some agronomic measurements, such as plant height, are not meaningful for comparison between crops. However, it is necessary to study the number of green leaves on the plant, and leaf area (e.g. LAI) because they are of primary importance for photosynthesis, by capturing the sunlight during the growing period. There is a strong relationship between the rate of dry matter production by crops and the accumulated intercepted radiation under non-stressed environments (Monteith, 1977). The slope of this relationship is called radiation use efficiency (Sinclair & Muchow, 1999). Importantly, the radiation use efficiency is largely different from the leaf appearance rate (Fletcher et al., 2012), so the earlier canopy closure is effective in a light interception and weed suppression (Seavers & Wright, 1999; Williams II & Boydston, 2013).

2.4.4 Phyllochron

The phyllochron is used to estimate the rate of leaf appearance in response to average temperature, calculated as the thermal time accumulation between the appearance of successive leaf (°Cd/leaf) (Chakwizira et al., 2016b). With the leaf development, it is interesting to look at the phyllochron development of forage crops (°Cday/leaf) with the thermal time in different locations. The shorter the phyllochron length, the faster the leaf development. Tsimba et al. (2013c) stated that the average phyllochron for maize is 47°Cd/leaf, but this varied with different soil temperatures, radiation, and moisture from emergence to tassel initiation. Winter forage kale and swede approximately reached the canopy closure about ~500 °Cd, with the phyllochron length of 47°Cd/leaf for kale and 51°Cd/leaf for swede (Fletcher et al., 2012). A longer phyllochron of 110 for kale was recorded too with the calculation of T_b = 0 °C (Wilson et al., 2004). For fodder beet, the phyllochron was 48-53°Cd/leaf in non-water stressed crops and 60°Cd/leaf in water-stressed conditions (Chakwizira et al., 2016b). Water stress influenced leaf development and its phyllochron length in forage crops (Chakwizira et al., 2016b; Tsimba et al., 2013c).

2.5 Feed quality of forage crops

Cows have high nutrient requirements to produce protein and fat. Depending on age, milk production, stage of pregnancy, and body condition goals, an average cow (~450 kg liveweight) in NZ may require 9 – 15 kg DM daily to meet the approximate daily energy requirement of ~110 – 132 MJ ME/kg DM (DairyNZ, 2021; Moran, 2005).

This energy is used for cow maintenance and production. In addition, cows require high protein diets particularly during lactation while fibre is important for rumen function (Moran, 2005; Waghorn, 2007). The qualitative attributes of forage crops are important to ensure animal nutritional requirements are met. Among them, metabolizable energy (ME), crude protein (CP), acid detergent fibre (ADF), neutral detergent fibre (NDF), soluble sugars and starch (SSS) are the main quality attributes for animal feed, so are primarily focused on in this study. Other macro and micro minerals are also essential for the evaluation of feed quality due to their importance in the normal growth and reproduction of animals but are not discussed in this study (National Research Council, 2001; Waghorn & Clark, 2004).

2.5.1 Metabolisable energy

Beyond the assessment of DM yield, farmers and agronomists look at the metabolizable energy (ME) content of forage crops to estimate the energy source available for animals. Metabolisable energy is a measure of energy and is calculated as the energy in feed (gross energy) minus the energy lost in faeces, urine, and methane (Waghorn, 2007; Waghorn & Clark, 2004). Thus, it represents a portion of the feed energy that can be utilised by the animal expressed as MJ/day or MJ/kg DM (Alderman & Cottrill, 1993). The ME value is accepted as the best overall measure of feed value, although no one measure gives a complete picture (White et al., 1999).

Metabolisable energy values differ among the crops used in this research. For example, good quality maize silage requires an ME content of about 10.8 MJME/kg DM (Kolver et al., 2001) but ME content can range from 10.3 to 11.3 MJ/kg DM with significant differences among maize hybrids and consequently affect total ME yield/ha Millner et al. (2005). The ME content of forage brassicas is generally higher than maize silage being approximately 13 MJ/kg DM for kale and swede (White et al., 1999). Fodder beet crops also have a comparatively high ME content (~12.5 MJ/kg DM) due to the high carbohydrate content of the storage root (Chakwizira et al., 2014a; Gibbs, 2014; Matthew et al., 2011).

Although forage ME values of some crops are high, the total energy value per hectare (ME × Biomass yield/ha) depends on the biomass yield. For example, in a cropping sequence over five years in Taranaki, the accumulated energy value (ME × crop yield/ha) of maize (171-350 GJ/ha) was found to be higher than that of other crops, such as turnips (133 GJ/ha), spring rape (143 GJ/ha), triticale (108 GJ/ha), barley (137 GJ/ha), and oats and Italian ryegrass (30 GJ/ha) (Macdonald et al., 2012). Moreover, the same authors highlighted that maize could be the best crop for meeting energy deficits due to easy storage before use.

2.5.2 Crude protein

Crude protein in forages includes both protein and non-protein N (National Research Council, 2001). Crude protein can be calculated by multiplying N% by 6.25 (Islam & Garcia, 2012; Millner, 1993; National Research Council, 2001). In general, grasses and legumes are high in protein, especially associated with a higher proportion of non-protein N. Grains are less in proteins (depending on species) (Chaves et al., 2001; National Research Council, 2001). In most cases, when forages mature fibre content increase and dilute CP (Waghorn & Clark, 2004).

Forage CP generally respond to the available N (soil or fertiliser) uptake by the plants. However, research has shown that N fertilisation did not consistently affect CP values of chosen forage crops. For example, Chakwizira et al. (2015b) found N application (0-500 kg N/ha) did not affect CP in kale crops in Lincoln, NZ. Furthermore, Chakwizira et al. (2014a) observed that N rates (0 to 200 kg N/ha) did not significantly change CP content in fodder beets in NZ. In contrast to these research findings, CP values change with an additional N fertiliser and delay sowing time on several forage crops tested in Waikato and Canterbury (de Ruiter et al., 2019). The authors suggested that the late sowing may have interactions with other factors, probably due to the later N uptake and accumulation of soil N through mineralisation. Similarly, CP was increased in fodder beets with about the same N rates (0 to 200 kg N/ha) in Turkey (Albayrak & Yuksel, 2010; Turk, 2010). Baghdadi et al. (2017) reported that higher N applications had a significant increase in the CP content of maize in Iran.

2.5.3 Soluble sugars and starch

Soluble sugars and starch (SSS) are the components under non-structural carbohydrate (NSC) (National Research Council, 2001; Waghorn & Clark, 2004). Carbohydrates are the major source of energy in diets fed to animals, mainly for rumen microbes and host animals (National Research Council, 2001). They are almost entirely digestible compared to structural carbohydrates (ADF and NDF) (Villalba et al., 2021). Depending on species, these cell-content carbohydrates fractions would vary. For grasses, sucrose and fructans are major components while sucrose is the main constitute for beets and citrus pulp. For maize and grain crops, starch is the major form of carbohydrate (Miller & Hoover, 1998; Villalba et al., 2021; Waghorn & Clark, 2004).

Delayed harvest timing and high plant population increased a net change in the SSS content of forage crops in Waikato and Canterbury (de Ruiter et al., 2019). The key quality indicator to reduce nitrogen leaching is the high SSS (carbohydrate): CP ratio. When feed with high SSS is fed to cows the fibre contents become important for maintaining normal rumen function (Dalley et al., 2017). Feed that has a high content of sugars with low NDF has potential for rumen acidosis, due to a rapid accumulation of volatile fatty acids (VFA) reducing a rumen pH (Gibbs, 2014; Matthew et al., 2011; Nichol et al., 2003).

2.5.4 Fibre

Fibre is referred to as the dry mass of plant cell walls and is composed of cellulose, hemicellulose, and lignin. Plant cells of forage biomass are characterized as structural carbohydrates (cell wall) and cell contents (starch, sugars, organic acids, soluble protein) (Villalba et al., 2021). During chewing, the cell wall (fibre) is broken into small pieces to enable the digestion of cell contents by rumen microbes and to pass indigestible residue (lignin) to the intestine and pass out of the rumen as feces (Waghorn, 2007; Waghorn & Clark, 2004). Chewing allows passage and digestion of feed, and then the ‘space’ available in the rumen for more feed to be eaten (Waghorn, 2007). Less fibre feed means less chewing. Thus, fibre is essential to encourage salivation, and thereby maintain rumen pH (Waghorn & Clark, 2004).

Acid detergent fibre (ADF) represents a measure of slowly digested structural or cell wall carbohydrates, which includes cellulose and lignin as primary components but does not include hemicellulose (National Research Council, 2001; Villalba et al., 2021). Neutral detergent fibre refers to the total cell wall content and measures the structural carbohydrates in plant cell walls (i.e. cellulose, hemicellulose, and lignin) (National Research Council, 2001; Villalba et al., 2021). The difference between NDF and ADF is hemicellulose (Villalba et al., 2021; Waghorn, 2007; Waghorn & Clark, 2004).

In general, maize has a higher content of NDF while winter forage crops (kale, swede and fodder beet) are low in NDF values (Matthew et al., 2011; Westwood & Mulcock, 2012). The effect of agronomic management was to vary the fibre contents of forage crops depending on the crop type and experimental locations. For example, N applications did not affect ADF and NDF contents of maize cultivars in Ireland (Lynch et al., 2013) as well as kales and fodder beets in NZ (Chakwizira et al., 2014a, 2015b). However, a significant increase in fibre (ADF and NDF) contents was observed in maize with the N fertiliser application in Iran (Baghdadi et al., 2017). Likewise, a decrease in fibre content (ADF and NDF) resulted from the earlier harvest of maize hybrids (Lynch et al., 2012).

Overall, the effect of agronomic management (N fertilisation, irrigation, harvest timing) on the crop qualitative traits seems to depend on the climatic factors as well as the type of crops/cultivars. Therefore, it would be interesting to see if there are any differences between the forage cultivars chosen across different environments in NZ. Data on the change in feed quality as a result of agronomic factors (i.e. irrigation, N fertilisation and site differences) is still limited in the chosen forage crops, particularly kale, swede, and fodder beet in NZ and overseas.

2.6 Environmental factors on crop production

Environmental factors including climate and soil type play an important role in crop production. However, rainfall and temperature are emphasised in this research as the environmental factors for the forage crops production since the changes in these factors are likely to be the main challenge and drivers of the productivity and profitability of the dairy farms at present and in the future. The effect of these factors on crop production, rainfall and temperature ranges at experimental sites and their future trends in the country are discussed below.

2.6.1 Rainfall

Rainfall is the primary factor of importance in crop production. The mean annual rainfall generally ranges from 350 to 4000 mm in NZ but the highest rainfall often falls on the western flanks of the Southern Alps (>10,000 mm annually). Many areas receive greater than 1000 mm of rainfall in the North Island but some parts of Hawke's Bay, Whanganui, Manawatu and Wairarapa areas only receive rainfall from 750-1000 mm in a year. The rainfall amount has a wider gap in the South Island, about 350 mm in Central Otago to approximately 4000 mm in the western parts of the South Island (Macara, 2018). These rainfall amounts and distribution play an important role in NZ's farming, for example, the rainfall amount within spring and summer explained approximately 60% of pasture production in the simulated polynomial regression model with a Geographic Information System (Zhang et al., 2007).

Rainfall changes were estimated to impact in both positive and negative ways on agriculturally based industries in NZ (Dynes et al., 2010b; Kalaugher et al., 2017; Macara, 2018; Zhang et al., 2007). For example, five climatic zones were defined for the North Island based on the rainfall and temperature ranges (Zhang et al., 2007). Under the eight predicted scenarios, the pasture production changes were from -20.4 to +9.6% on average across all the North Island regions. The author also mentioned that climate change will affect pasture production with a decrease in -2.3 to -27.3% in the north and north-west; -3.8 to -22.0% in the south-east and an increase in +11.1 to +51.9% in the south-west of the North Island.

In the future climate, annual rainfall will increase 5-7.5% on the west coast of the South Island and some parts of Central North Island while the east coast will be dry (0-5% less rain) in the 2030-2049 projection based on the 1980-1999 baseline. However, most regions of the North Island will be drier (0-10% decrease in annual rainfall) in the 2080-2099 scenario (Figure 2.1) (Clark, 2012; Ministry for Primary Industries, 2020b; NIWA, 2008). This trend was also observed in the six site-specific simulations by Kalaugher et al. (2017), in which the annual rainfall changes were small and the North Island sites (Northland, Bay of Plenty, Waikato and Taranaki) were expected to receive less monthly rainfall in an A2 scenario (high CO_2 emissions) and higher monthly rainfall in B1 scenario (low CO_2 emissions) compared to the baseline rainfall (1980-2000).

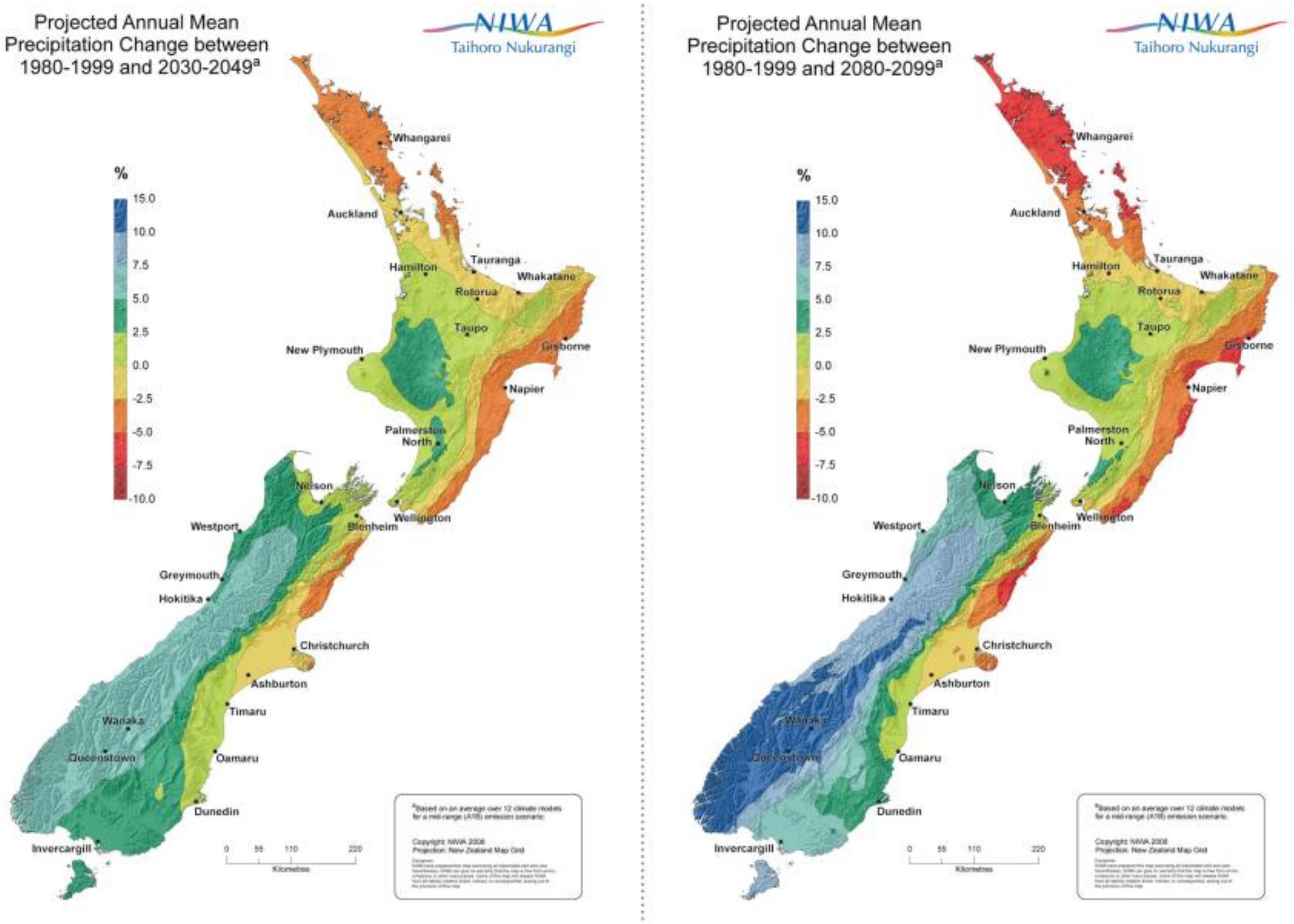


Figure 2.1. Projected annual mean rainfall change for 2030-2049 and 2080-2099 based on 1980-1999 climate (Source: NIWA, 2008).

The experiments in the current study are conducted in Manawatu and Waikato areas where intensive dairy farming is practiced. Annual rainfall ranges from 900-1,000 mm in Palmerston North, Manawatu (Chappell, 2015) and 1,200-1,600 mm in Hamilton, Waikato (Chappell, 2013). However, the seasonal rainfall was relatively lower than the long-term mean rainfall in both regions during the experimental periods (2018 - 2020) as the NIWA recorded as 4th and 7th warmest years for 2019 and 2020, respectively (NIWA, 2019, 2020). Dry spells, consecutive days less than 1 mm of rain, perhaps occurred on average for two periods per year (19 days average) in Palmerston North (Chappell, 2015) and one each year (20 days average) in Waikato between December and March (Chappell, 2013).

Extreme events of rainfall, either less or heavy, can harm crop performance. Heavy rainfall can induce excess soil water above the field capacity, resulting in waterlogging. The waterlogged condition can seriously affect the ability of the root in gaseous exchange and consequently the overall crop performance (Ashraf & Habib-Ur-Rehman, 1999; Kaur et al., 2020). On the other hand, reduced rainfall cannot provide the required amount of soil water to the plants. If this situation persists too long, plants can suffer from moisture stress by the prolonged dry periods. This can seriously affect crop production unless irrigation is managed.

The optimum rainfall within the crop growing season enables the plants to perform well and enhances crop productivity. Optimum rainfall can be considered as the amount of rainfall that can replenish the soil water losses by evapotranspiration. This means that the soil could maintain the soil water at field capacity in the soil so that the plants can easily obtain the profile available soil water.

2.6.2 Temperature

Temperature is a key factor influencing plant growth, especially during winter and early spring in NZ. In general, the temperature ranges from 18℃ to 24℃ in the summer afternoon and from -2℃ to 8℃ in winter overnight temperature. The mean monthly air temperature is highest in January-February and lowest in July. The mean annual average temperature ranges from 9℃ to 15℃ in the North Island (Macara, 2018; Zhang et al., 2007) and 2℃ to 14℃ in the South Island (Macara, 2018).

An increase in temperature is likely to happen in the future, which will affect crop production in NZ. The annual mean temperature is projected to increase about 1℃ in 2030-2049 and about 2.2℃ in 2080-2099 in most parts of the North Island while varying from 0.75-0.95℃ in 2030-2049 and about 2.0-2.1℃ in 2080-2099 in the South Island (Figure 2.2) (Ministry for Primary Industries, 2020b; NIWA, 2008). It has been expected 0.5℃ warming more since 1950 in NZ assuming a 0.13℃ warmer rate per decade globally (Fitzharris, 2007). This warming weather results in fewer frosts, increasing the intensity of droughts and variation in rainfall. Such changes were expected to increase faster in the North Island than in the South Island, with rainfall likely to increase in the west of the country and decrease in the east (Ministry for Primary Industries, 2020b).

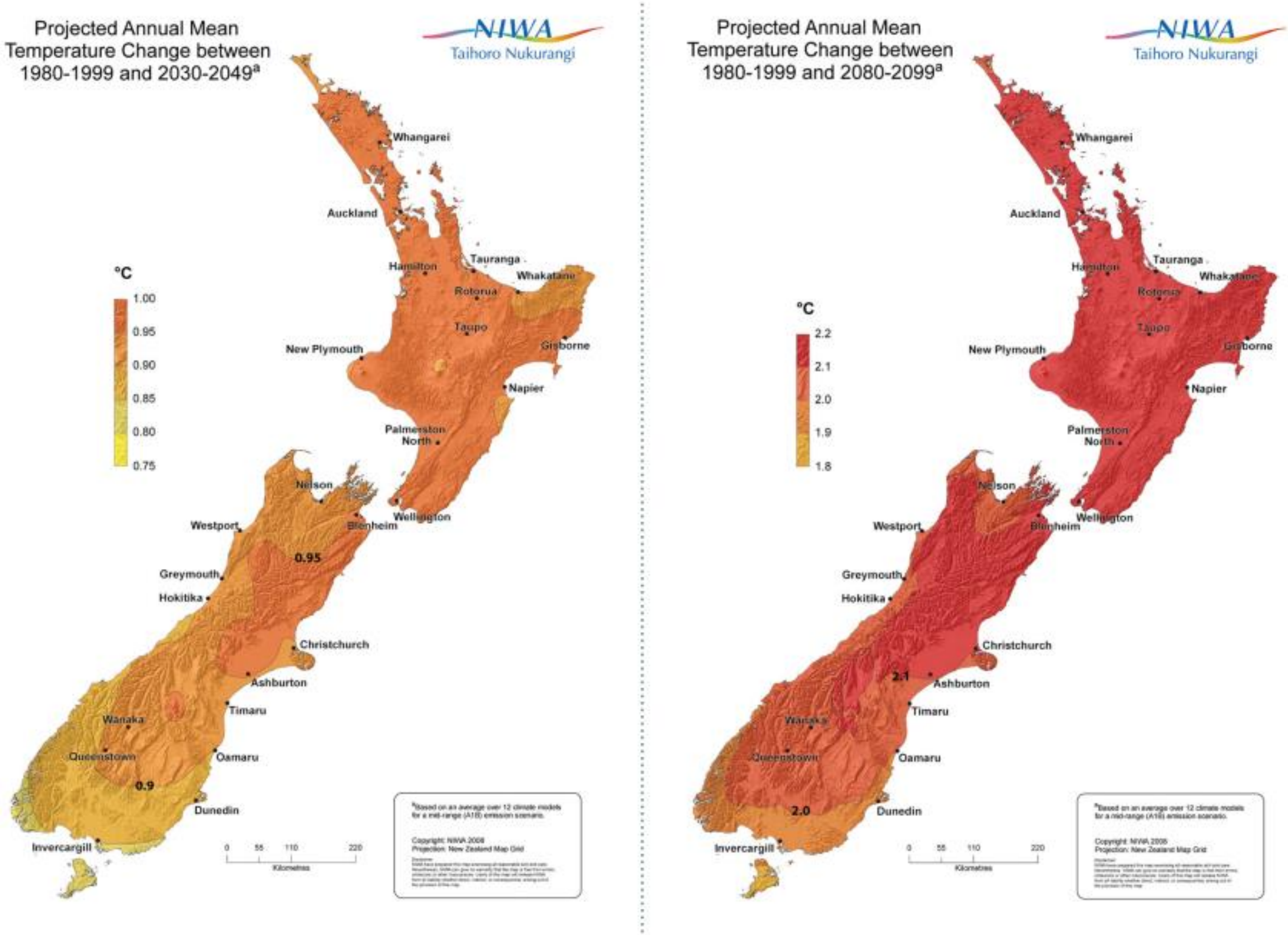


Figure 2.2. Projected annual mean temperature change for 2030-2049 and 2080-2099 based on 1980-1999 climate (Source: NIWA, 2008).

From a positive point of view, the increased temperature with increasing CO_2 levels could enhance the progress of crop developmental phases faster, with an estimated 30% increase in crop growth rates in wheat (Jamieson et al., 2000) and an increase in the yield of barley, oats, wheat and forage maize (Morel et al., 2021) and potato (Dynes et al., 2010b). About 90% of the yield variation was caused by temperature with the increased CO_2 level rather than rainfall in a simulated APSIM model (Morel et al., 2021). The faster crop growth cycle will also give more opportunities to grow the subsequent crops due to the chance of earlier harvest.

Moreover, a warmer environment will be suitable for the cultivation of frost-sensitive crops in frost prone areas and warm-season crops in a wider range of sites, particularly the southern locations in NZ (Dynes et al., 2010b). In addition, the planting window for crop cultivation can be probably extended with agronomic management. This highlights the importance of forage crops which has been found to be a more suitable and viable crop option in temperate countries, like Sweden (Morel et al., 2021) and NZ (Southern latitudes) (Dynes et al., 2010b; Teixeira et al., 2012) with the increased temperature changes of climate scenarios.

From a negative point of view, the seasonal timing of crop production needs to be adapted and more frequent severe droughts will occur and the changes in management practice will need to cope with the dry seasons. Deeper rooted crops would be needed for the efficient use of water (Ministry for Primary Industries, 2020b).

2.6.3 Thermal time

Crop growth and development depend on the thermal time accumulation throughout the growing season. Thermal time, otherwise known as the growing degree day or heat unit, is used to estimate the timing of important growth stages of crops (Tsimba et al., 2013c) and to attain the best outcome from crop management, such as fertiliser application, harvest timing and pest control. The cardinal temperature for thermal time accumulation is different for the crops chosen for this research. Thermal time is calculated with the following formula:

$$TT = \left[\frac{(Tmax + Tmin)}{2}\right] - Tb$$

where, T_{max} = daily maximum temperature

T_{min} = daily minimum temperature

T_b = base temperature

The base temperature (T_b) differed with the crops, growth stages and locations. The common base temperatures of forage crops chosen for this research are outlined. The base temperature (T_b) for maize silage in NZ is 8°C (Tsimba et al., 2013c) whereas T_b 6-9°C has been used in some countries, for instance in the US (Vinocur & Ritchie, 2001). Again, T_b for the forage brassicas is normally in the range from 3.5 to 4°C (Adams et al., 2005; Andreucci et al., 2016; Fletcher et al., 2012), mostly ≤4.5°C for temperate species (Lonati et al., 2009), and it is slightly lower for the bulb type brassicas, such as swedes. However, the T_b = 4°C has most used for forage brassicas in NZ (Andreucci et al., 2012; Andreucci et al., 2016; Fletcher et al., 2012; Wilson et al., 2004). For fodder beet, the alternatives of 0°C (Chakwizira et al., 2016b) and 3°C (Chakwizira et al., 2016b; Martin, 1986; Stocker et al., 2016) have been used for the calculation of thermal time. However, Chakwizira et al. (2016b) found that T_b = 0 is the highest R^2 value for the linear relationship between the number of leaves per plant and thermal time accumulation. Hence, to estimate the appropriate thermal time calculation, the base temperature (T_b) is considered as 8°C for maize silage, 4°C for forage brassicas and 0°C for fodder beet in this research.

2.7 Management factors on crop production

As crop production depends on climatic factors, management and adaptations need to be practised accordingly to maximise productivity and profitability in farming. Of many adaptations based on the regional climatic projections (Dynes et al., 2010b; Hennessy et al., 2007; Zhang et al., 2007), irrigation and fertiliser management are emphasized in this review because they are important current necessary interventions in the crop production of the dairy industry. Irrigation and fertiliser management are likely to impact farm production at present and in the future to adjust the profitability and environmental costs associated with farming in NZ. Thus, their effect on crop production and environmental impacts are summarised below.

2.7.1 Irrigation

Irrigation has increased in agriculture in NZ over the last 20 years. Farmers have adopted irrigation due to increased summer drought and higher potential profitability of irrigated farms (Aqualinc, 2010). There were 720,000 ha of irrigated farmlands in NZ in 2012 which increased to 903,465 ha in 2020 (Dark, 2020). Half of the irrigated land is used for dairy farming in NZ (IrrigationNZ, 2021; Muller et al., 2021). Most of the irrigated area (77%) is in the drier east coast regions of the South Island: 60.5% (546,205 ha) in Canterbury, 12.3% (111,082 ha) in Otago and 3.9% (35,351 ha) in Marlborough of the total irrigated area 903,465 ha in NZ (Dark, 2020; Dynes et al., 2010a). With increasing irrigation, spray irrigation systems (compared with wild flooding and border dyke) are becoming dominant, accounting for 95% of the irrigated area (Dark, 2020).

Irrigation increases crop yields. For example, irrigation (0-480 mm) increased maize DM yield from 9.3 to 23.8 t/ha in Australia (Islam et al., 2012). The authors highlighted that yield increase was related to increased grain content (92 to 315 g/kg DM) but reduced stover content (all remaining parts plus cobs excluding grain). Similarly, full irrigation (200 mm) produced a higher biomass yield for silage maize (24.3 t DM/ha) compared with restricted irrigation (50 mm) (17.8 t DM/ha) (Gallo et al., 2014). Likewise, irrigation improved the radiation use efficiency of the crop through the faster and longer critical leaf area index of fodder beet, which enhanced the yield increase at the final harvest (Chakwizira et al., 2018).

Irrigation also affects the quality of forage crops but is often inconsistent and associated with other managements or attributes. Irrigation can increase the NDF content of maize silage but reduce CP, water-soluble carbohydrate (WSC) and ME content. Decreasing ME may be the result of a negative association between NDF and grain content of the silage. Increased cell wall contents (i.e. NDF) mean a decrease in cell contents (i.e. CP and WSC). Likewise, remobilisation of N from leaf and stems (temporary reservoirs) to the grains is one possible reason for decreasing CP because grains formation occurred steadily under well water conditions (Islam et al., 2012). In contrast, Gallo et al. (2014) reported that the starch content of maize was increased with full irrigation (200 mm) while starch was reduced under restricted irrigation (50 mm). Additionally, the lower CP in winter forage crops under irrigation has been reported previously (de Ruiter et al., 2019). The authors explained that it is a general dilution effect between CP and SSS, a net change in SSS accumulation with delayed harvest reduces CP content (de Ruiter et al., 2019). On the other hand, irrigation effect on plant component's contribution to final yield could change forage qualities, for example, leaves are higher in protein than the stems in forage brassicas (Pelletier et al. 1976 cited in Chakwizira et al., 2015b).

Good management of irrigation is crucial to get maximum growth responses as well as to minimize the losses of nutrients from the root zones. Crucially, irrigation should match crop demand (Thomas et al., 2006) using irrigation frequencies which ensure that soil can maintain relatively large soil moisture deficits even after irrigation (Thomas et al., 2016). Vogeler et al. (2019) assumed no irrigation is required whenever the preceding day's rainfall exceeded 5 mm. They also recommended less frequent irrigation based on APSIM modelling results, not only to reduce N losses without compromising pasture production but also to maintain soil water deficits.

2.7.2 Irrigation and N leaching

Irrigation may change soil processes in the long term. Long-term irrigation can improve the water-holding capacity of the soil, thereby reducing drainage (Drewry et al., 2021). The risk of irrigation-induced drainage is high from March-May while the risk of rainfall-induced drainage is high from May to July in NZ (Muller et al., 2021). Herzig et al. (2016) used a land-use management support system (LUMASS) to predict the effect of irrigation and intensification of land use in the Ruamahanga catchment in NZ. The intensification scenarios for dairy farming and arable cropping increased milk solid production across all five scenarios but also nitrate leaching and greenhouse gas emissions. Irrigation enables greater crop and pasture production, which may lead to a higher stocking rate, resulting in a greater risk of urine deposition and nitrate leaching. For example, Gheysari et al. (2009) measured nitrate leaching under a maize silage crop with different irrigation levels and nitrogen fertiliser application rates. They found that nitrate leaching ranged from about 8.4 kg N/ha of nitrate from the upper 60-cm while 40.8 kg N/ha leached from the upper 30-cm under low and high irrigation rates, respectively.

2.7.3 Nitrogen fertiliser management

Nitrogen is the most responsive nutrient in crop cultivation in NZ. Nitrogen fertiliser application increased about 60-fold from 1961 to 2001 in NZ (MacLeod &

Moller, 2006). Total N application increased from 59,265 tonnes to 376,890 tonnes between 1990 and 2014 (Ministry for the Environment, 2016). In addition to observing the N effect, it is also necessary to determine the optimum amount of N application not only to meet peak farm production levels but also to reduce environmental risks. The application of N fertiliser, the optimum rate and the response of maize, fodder beet and forage brassicas are briefly discussed in the following sections.

2.7.3.1 Standard N rate for maize silage

The amount of N required by maize crops varies depending on the soil type, soil background N, crop removal and yield potential. Compared to grain maize, silage maize requires more N and K fertiliser because the stover is usually removed from the paddock after harvest. The addition of 155-245 kg N/ha annually is recommended if yields >22 t DM/ha of maize silage for soils with low background soil N are to be achieved (Li et al., 2006). The amount of N fertiliser used for maize silage in NZ is similar to that used for commercial corn production in the Midwest region of the US (Dinnes et al., 2002). In NZ, Genetic Technologies Limited (Pioneer Brand NZ) recommends N inputs based on yield potential at a rate of 12.8 kg N/t DM/ha maize silage yield. For example, a 22 t DM/ha maize silage crop will require a total of 280 kg N/ha (soil + applied fertiliser N). This is consistent with other studies showing that a 21 t DM/ha maize silage crop removes 273 kg N, 63 kg P, 210 kg K and 13 kg S per ha (Nicholls et al., 2012). Fertiliser rate could be reduced if maize silage is grown on paddocks with high background mineral N or effluent applied paddocks (Williams, 2012).

2.7.3.2 Standard N rate for brassica crops

Many fertiliser trials comparing different N and P application rates have been conducted for winter forage crops in NZ (Chakwizira et al., 2011a; Stevens & Carruthers, 2008; Wilson et al., 2006). Chakwizira et al. (2011a) suggested that the most economical N rate for swedes in NZ was 150 kg N/ha, although responses were variable across sites. However, the highest yield in their study was observed at 300 kg N/ha suggesting that optimum N fertiliser rates may be higher depending on the crop species, climate, and soil background mineral N.

Stevens and Carruthers (2008) tested N rates of 0, 100, 200, 300 and 400 kg N/ha for kale and swede in Palmerston and Stoneburn (Northeast Otago), where the environment is often too dry in mid-summer. They found that nitrogen rates between 200 and 300 kg N/ha produced the peak yield for kale and swede crops. Similarly, application rates of 200-300 kg N/ha are generally recommended for soils with low soil N (<100 kg/ha) to achieve potential yields of 15-22 t DM/ha for swede and kale crops (Morton et al., 2017).

2.7.3.3 Standard N rate for fodder beet

There have been fewer studies investigating the N requirement for fodder beet in NZ compared with brassica crops. A general recommendation of 100 kg N/ha for fodder beet to obtain optimum yield in NZ where soil N levels are high, e.g. following pasture (136 kg N/ha) has been made (Chakwizira et al., 2014a, 2016a). These authors found little response to N rates of 50 kg N/ha and above under dryland conditions, whereas with adequate irrigation yield responses occurred at up to 200 kg N/ha. However, it is possible that responses to higher rates could have been obtained. Morton et al. (2017) recommended adding about 200-225 kg N/ha to achieve the potential yield of 25-30 t DM/ha of fodder beet.

2.7.4 Validation of standard N rate with crop N

To validate the standard N rate, the required amount of N fertiliser can be estimated with the actual crop N and potential crop yield, using the relationship described below.

[Biomass yield of component (kg/ha) × (N%/100)] (de Ruiter et al., 2009b)

The potential yield, the ratio of plant components to total DM yield and its percentage of uptake N are given in Table 2.2. These data are obtained from previous research and seed suppliers in NZ (Anon., 2018). Sections (2.7.3.1 to 2.7.3.3) indicate that N application rates between 200 to 300 kg N/ha are appropriate for high yielding forage crops. The estimates of N requirements in Table 2.2 are higher but are based on potential yields and total N uptake taking into consideration soil N, rather than fertiliser application.

Table 2.2. Percentage of component contribution to total yield, its N uptake and required N rates to achieve the potential yield of forage crops.

Crop/ Plant parts	**% Contribution to total yield[a]**	**N%[b]**	**potential yield (t/ha)[c]**	**Total N accumulation in plant components (kg/ha)**	**Reference**
Maize					
leaf	10.3	2.19	2.6	56.94	(Millner et al., 2005)
stem	25.3	0.34	6.3	21.42	(Millner et al., 2005)
grain	46.0	1.57	11.5	180.55	(Millner et al., 2005)
cob	17.65	0.46	4.4	20.24	(Millner et al., 2005)
Total			~25	279.15	
Kale					
leaf	35	3	6.3	189	(de Ruiter et al., 2009b; White et al., 1999; Wilson et al., 2004)
stem	60	1.75	10.8	189	(de Ruiter et al., 2009b; Wilson et al., 2004)
Total			~18	378	
Swede					
leaf	25	3	4.5	135	(Chakwizira et al., 2011a; de Ruiter et al., 2009b; White et al., 1999)
bulb	70	2	12.6	252	(de Ruiter et al., 2009b; Gowers et al., 2006)
Total			~18	387	
Fodder beet					
leaf	15	2.09	2.7	56.43	(Boclaci & Cremeneac, 2016; Chakwizira et al., 2016a; Morton et al., 2017)
bulb	80	2.3	14.4	331.2	(Chakwizira et al., 2016a; Chakwizira et al., 2018; Gibbs, 2014)
Total			~18	387.63	

[a & b] Relative contributions of each component and % N are retrieved from previous research
[c] Crop potential yield is obtained from seed suppliers and previous research in New Zealand

2.8 Wintering system and its impact on the environment

2.8.1 Wintering systems

Among different kinds of winter management (Pinxterhuis et al., 2013), *in situ* wintering on forage crops can be seen as intensive winter grazing. Intensive wintering is defined as, "*a farming practice where livestock (cattle, sheep, deer) are confined over* *winter to outdoor feeding areas planted with annual forage crops (e.g. swedes, kale and fodder beet)"* (Ministry for the Environment and Ministry for the Primary Industries, 2021). The winter management of dry dairy cows is critical to the profitability of the whole farm system, especially in the South Island. The grazing of cows on annual forage crops is one of the main activities in the winter management in NZ dairy farms since these crops are supplementary to the pasture-based dairy systems. The consequences of the low temperatures (common in Southland and Otago especially) resulting in the low pasture growth are that farmers need to have dairy support blocks on which forage crops (kale, swede, and fodder beet) are grown to fill winter feed deficits (Dalley et al., 2020a; Gibbs, 2014; Pinxterhuis et al., 2013).

Wintering livestock is challenging for the farmers due to the trade-off between animal welfare and environmental risks. Challenges include ensuring sufficient feed supply, cost contribution, allocation of feed to livestock, animal welfare, farm labour and the environment (Dalley et al., 2013). Winter nutrition influences animal welfare, growth performance, milk production and reproductive performance (Dalley, 2011; Pinxterhuis et al., 2013). For many dairy farmers achieving a body condition score (BCS) at a calving of 5 to 5.5 (Roche et al., 2009), high-quality winter supplementary feed is required (Dalley et al., 2020a).

However, wintering livestock on forage crops can cause negative environmental impacts. Intensive grazing over winter for extended periods removes the vegetative cover, resulting in increased runoff and discharge of nutrients, sediments and microbial pathogens into surface water and groundwater. This causes serious negative impacts on freshwater in particular (Ministry for the Environment and Ministry for the Primary Industries, 2021). Risks are greater in wet weather and include waterlogging, pugging, surface run-off and sediment loss on heavy soils while on lighter soils more prone to downward movement of water, nitrate leaching into groundwater is a problem (Ministry for Primary Industries, 2021). Changes in soil properties such as increased soil compaction with lower microporosity and greater bulk density are also common in intensively grazed winter crops (Chamen et al., 2015; Drewry et al., 2021; Houlbrooke et al., 2009; Laurenson & Houlbrooke, 2016).

Mitigation strategies to reduce the potential environmental effects of wintering systems in NZ have been initiated by the Local and Central Governments resulting in regulations which restrict the amount of nitrate able to be leached. For example, increasing scrutiny from the New Zealand public (Dalley, 2011) has resulted in the NZ government putting in place minimum standards around intensive winter grazing from May 2022 (Ministry for Primary Industries, 2021). It is estimated that approximately 240,000 ha was used for winter grazing of forage brassicas crops in NZ in 2018 (Ministry for the Environment and Ministry for the Primary Industries, 2021). In some areas of NZ, Government regulations are set to restrict the intensive winter grazing of annual forage crops. For example, the total area intensively grazed must not be greater than 50 ha or 10% of the farm area (whichever is greater) and the mean slope angle of the cropped land must not be greater than 10 degrees; there is some consultation over potentially increasing the maximum mean slope to 15 degrees (Ministry for the Environment and Ministry for the Primary Industries, 2021).

2.8.2 Potential N leaching risks from grazed wintering systems

This research aims to estimate the potential nitrate leaching risk from two alternative systems: one representing a cut and carry system (maize silage) and the other an *in situ* grazed wintering system (winter forage crop grazing) for different crops under different management (irrigation/fertilisation). The potential risks of N leaching through a deposited urine N via feeding of these crops will be predicted using modelling studies.

The Ministry of Agriculture and Forestry Monitor Farm Model indicates mean N leaching losses of 38, 12 and 8 kg N/ha/year for dairy, deer and sheep/ beef farms respectively (MAF, 2008 cited in Quinn et al., 2009). Accordingly, dairy farming has been identified as the relatively high nitrate leaching sector in NZ (Ledgard et al., 2000; Pinxterhuis et al., 2015). These N losses can cause elevated concentrations of nitrate-N in water (Malcolm et al., 2014) and consequently, impact water quality for human consumption (Ledgard et al., 2000).

In a grazed wintering system, nitrate leaching losses are likely to occur during the fallow period (Edwards et al., 2014a; Malcolm et al., 2016b), three to five months after grazing winter forage crops such as swede, kale and fodder beet (Malcolm et al., 2017). The main reasons for nitrate leaching losses in these systems include high stocking density resulting in urine patches (Edwards et al., 2017; Malcolm et al., 2017), forage residues left-over after grazing due to trampling and lower crop utilisation (DairyNZ, 2013; Rugoho, 2013; Thompson et al., 2012), high rainfall and lack of active plants to take up residual N (Malcolm et al., 2017). When high yielding crops are grazed a large amount of N is excreted over a short period, elevating the risk of leaching.

A range of strategies have been identified to solve nitrate leaching losses but some are not economically viable, for example, off-farm cow housing (Edwards et al., 2017). Similarly, an on-farm solution such as growing catch crops after winter grazing needs timely sowing for good establishment under field conditions (Malcolm et al., 2016b), so is an unreliable option under irregular rainfall environments. The wet soil after grazing also needs a considerable time to let the soil dry for replanting a new crop, so immediate sowing of a cover crop is not practically feasible in grazed paddocks without proper machinery, such as a Spader-drill (Carey et al., 2022).

Maize silage could be used to provide an alternative winter-feeding strategy which avoids high densities of grazing animals for extended periods (Pacheco & Waghorn, 2008; Snow & White, 2013). Moreover, being a low-N forage, maize silage is able to reduce urinary N excretion (Pacheco & Waghorn, 2008). There is little research published assessing whether it is feasible to feed maize silage over the winter to reduce nitrate leaching risks compared to grazing winter forage crops such as kale and swedes.

2.8.3 Methods to estimate the N leaching losses

Nitrogen leaching is a complex process related to crops, livestock, soil, management practices, and weather in a seasonal or long-term period. As a result, N leaching can vary depending on these factors and whether the measurements are in the field or controlled environment (Ramos & Kucke, 2001).

To estimate N leaching losses, two methods may be used. One is a direct measurement of N leaching using instruments such as lysimeters or suction cup samplers placed into the soil at the leaching zone or under the roots zone, where most nutrients will drain with the soil water. Some N leaching loss measurement tools in NZ are described in the literature such as intact column lysimeters, repacked lysimeters, ceramic suction cups, and hydrologically isolated plots (Dennis, 2020). The other approach is to estimate potential N leaching by using a system modelling simulation software. Modelling is a good way to estimate N leaching to measure the effect of several different management strategies.

In this research, models will be used to estimate the potential N leaching risk from different crop types and management practices. The aim of the research is to better understand the potential risk of N leaching via deposited urine N posed by different feed options and the interactions between crops, management practices and the seasonal climate. The direct measurement of these factors would be difficult as well as very time-consuming. Modelling platforms such as APSIM, Overseer, DairyMod, and Farmax are currently widely used system simulators in international and NZ farming conditions.

Among several simulators, Overseer and APSIM models are thoroughly reviewed to use in this study. In Overseer, the model predicted well the nutrient losses from the total farm area and respective blocks. The model inputs such as soil information, climate, and basic farm structures are readily available and easier to simulate in the model. However, the protein or N content of forage crops is considered as an average value in the Overseer. For our purpose, we would like to directly use the N content of forage crops that resulted from field experiments conducted in different managements and sites, so the actual differences in forage N resulting from management effect can be seen in the model outputs. Therefore, we have chosen the APSIM model although it requires detailed model inputs such as soil data and climatic information.

2.8.4 APSIM

APSIM is a biophysical process-based model able to simulate the interconnection of the systems comprising soil, crop, tree, pasture, and livestock in response to management and climate (Holzworth et al., 2014; Holzworth et al., 2018). The framework is made up of several components, mainly biophysical modules, management modules, various modules that facilitate data input and output, and a simulation engine that drives the simulation process and facilitates communication between the independent modules (Holzworth et al., 2014).

The users can choose the sub-modules under plants, soil, animals, and management options to perform simulation on a paddock scale or the whole farm. The inputs are the climate data, soil profile data, management options for the crop (e.g. cultivars, fertiliser application, harvesting), and livestock (e.g. grazing, off-paddocks). Daily time-step of climatic data (rainfall, maximum/minimum temperature, solar radiation) is required to better estimation of crop growth and development. Likewise, detailed soil profile data (soil physical and chemical properties, soil water content of each horizon) should be defined as an initial input in the model (Cichota et al., 2021). The model outputs can be defined by the users in the 'Report' section of modelling, for example yield, crop growth parameters, accumulated thermal time, crop N, soil water content, soil N, drainage, and N leaching from specific soil layer, etc. The outputs are produced in a daily time step but can be transformed into yearly or specific periods. Details of the modules and modelling are referred to the APSIM website (https://www.apsim.info/).

APSIM is widely used in crop modelling worldwide since it is available to anyone for non-commercial use. The plant modelling framework in APSIM allows the users easy to construct and configure the crop models (Brown et al., 2018; Brown et al., 2014). APSIM has been used extensively in crop modelling and soil N prediction in NZ conditions (Beukes et al., 2011b; Giltrap et al., 2015; Khaembah et al., 2017; Moot et al., 2015; Sharp et al., 2011; Teixeira et al., 2010; Teixeira et al., 2011; Vibart et al., 2015; Watt et al., 2022). The model outputs are validated with field experimentations across the country (Khaembah et al., 2017; Sharp et al., 2011; Teixeira et al., 2018; Vibart et al., 2015), so the modelling results are reliable with the existing APSIM crop modules under the NZ context.

2.9 Summary and research gaps

Winter forage crops are an important source of supplementary feed for livestock, particularly dairy cattle in NZ. However, these crops can contribute to high N leaching loads, especially when grazed by cattle, including dairy cows. These forage crops are an important source of feed for livestock particularly in autumn and winter due to the shortage of pasture resulting from the slow growth in winter periods. On one hand, the herbage yield of these winter crops is a defining factor for the profitability of many dairy farms through the animal performance during lactation and when dried off. But they can potentially add significantly to the total N leaching of the whole farm. Wintering on these crops not only risks a serious problem of downward N leaching but also damage to the soil's physical and chemical properties in the long term. The strategies to reduce the total N leaching of the whole farm predominantly depend on how the farmers manage these paddocks on the farm. Alternative cropping options for producing supplementary feed in the winter are necessary to provide a long-term solution to the problem of providing supplementary winter feed with reducing the environmental impacts. The alternative cropping option should have a competitive advantage in yield and feed qualities but also suit NZ cropping systems while being able to cope with future climate change.

Based on the current literature, a side-by-side comparison of maize silage and winter forage crops has not been done in NZ. As the forage yield depends on the weather and locations, it is necessary to conduct the research in a wider range of sites which have differences in rainfall, temperature, and radiation levels so that a full picture of yield and quality differences could be seen between forage crops. Moreover, the effect of agronomic management (such as fertiliser application, and irrigation treatments) on yield and forage quality is still a knowledge gap for these crops in NZ. Finally, a field measurement or modelling comparison of N leaching losses from maize and winter forage crops together is still limited in NZ and overseas.

Chapter 3 Productivity and quality of kale, swede, fodder beet and maize in Manawatu and Tokoroa

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3.1 Abstract

Winter grazing of forage crops can result in large losses of nitrogen (N) from leaching and consequently, deterioration in water quality in affected catchments. A viable alternative cropping option which can potentially reduce N leaching may be useful for maintaining farm productivity while minimising environmental risks. Maize could be a possible alternative crop because of its yield and low N as well as convenience to cut and carry system. Thus, maize, kale, swede, and fodder beet were compared in a factorial randomised complete block design with or without N application. Dry matter (DM) yield ranged from 12,450 to 30,417 kg DM/ha with the highest yield achieved by maize hybrids at Palmerston North while yields at Tokoroa were not different. Yield ranged from 12,733 to 22,928 kg DM/ha at Tokoroa. Yield was increased by N application, but there was no interaction between forage entries and N rates at both sites. Feed quality was assessed at the Palmerston North site. Forage entries differed significantly in all quality traits while N application only affected crude protein (CP), soluble sugars and starch (SSS) and acid detergent fibre (ADF). Metabolisable energy (ME) was significantly different for all forage entries. It ranged from 9.5–11.0 MJ/kg DM for swede, fodder beet and maize and was <9.5 MJ/kg DM for kale. Maize hybrids showed the lowest CP (5.4–5.9%) and the highest SSS (42.7–48.0%). Dry matter yield was positively correlated with SSS ($r = 0.58$; $P<0.001$) and neutral detergent fibre (NDF) ($r = 0.56$; $P<0.001$). Similarly, ME was positively and strongly correlated with SSS ($r = 0.79$; $P<0.001$) while CP was negatively correlated with yield and all quality traits. Maize and fodder beet had high SSS:CP ratio's (>3), indicating good potential for reducing N excretion. The results highlight the advantages of maize having high DM yield and good feed quality (except a low CP) under unlimited moisture conditions at Palmerston North.

Additional keywords: beet, forage brassicas, dry matter yield, yield components, feed quality, maize silage, nitrogen, supplementary feed crops, leaf appearance

3.2 Introduction

Maize, fodder beet and forage brassicas are commonly used as feed crops in New Zealand (NZ), especially in winter feeding or as a supplement during summer drought periods when pasture growth is low or poor quality (Cheng et al., 2018; Fletcher et al., 2012; Wilson et al., 2006). As a supplementary feed crop, maize is particularly important in the North Island (Chakwizira et al., 2017b; Clark et al., 2007; Densley et al., 2006) while fodder beet, kale and swede are more important for winter grazing in the South Island (Gibbs, 2014; Malcolm et al., 2016a). High stocking density with high urinary N loading and high winter rainfall (Edwards et al., 2017; Malcolm et al., 2017) contributes to excessive N losses particularly if forage diets are high in protein. Nitrate leaching losses have been shown to occur in grazed wintering systems in NZ (Edwards et al., 2014a; Malcolm et al., 2016b, 2017). Nitrate leaching losses could be reduced using specific crop selections or using an integrated whole farm system approach (Edwards et al., 2017; Malcolm et al., 2016b). As urinary N excretion is directly related to N intake by animals (Kebreab et al., 2001), a possible strategy is to utilise crops that are high yielding and have low N content. It has been further suggested that there is potential to minimise N loading in paddocks by managing the composition of supplementary feed crops in animal diets (Dalley et al., 2020b; de Ruiter et al., 2019). The best cropping options for winter feeding may comprise a balance of *in situ* grazed crops and supplements. Differing feed allocations are required to reduce the environmental concerns and yet provide an economic yield while delivering suitable feed quality for animals. Therefore, the objectives of this study were (1) to compare the crop yield and feed quality of maize and traditional winter forage crops under different N treatments and (2) to identify cultivars for the following season's experiments in a greater range of environments in the lower North Island.

3.3 Materials and methods

3.3.1 Experimental sites

The trials were established at the Pasture and Crop Research Unit, Massey University, Palmerston North (40° 22′ 53″ S, 175° 36′ 22″ E) and Tokoroa (38° 10′ 49″ S, 175° 5′ 3″ E). The soil is a Manawatu sandy loam (Weathered Fluvial Recent soil) at Palmerston North and Horotiu silt loam (Typic Orthic Allophanic soil) at Tokoroa. A soil sample was taken on 11 October 2018 at Palmerston North and on 29 October 2018 at Tokoroa to assess soil fertility (Table 3.1). Soil samples were sent to Hill laboratories. Soil nutrients were converted into mg/kg of dry soil using the conversion factors: K × 20; Ca × 125; Mg, Na × 5 (Chapman & Bannister, 1994). The 150 kg/ha of Cropmaster 15 fertiliser (15% N, 10% P, 10% K, 7.7% S) was applied at planting (13 November 2018) to ensure adequate fertility for initial crop establishment at Palmerston North. No basal fertiliser was applied at the Tokoroa site.

Table 3.1. Soil characteristics before the experiment (0–15 cm depth) at Massey University and Tokoroa, New Zealand in 2018 – 2019.

Site	pH	Olsen P	K	Ca	Mg	Na	Mineral N	OM[a]
		mg/L		(mg/kg)			(kg/ha)	(%)
Massey	5.6	30	100	1125	115	30	93	3.9
Tokoroa	5.6	34	80	500	65	20	77	11.8
Optimum[b]	5.8–6.2	20–30	120–200	500–1250	≥50	10–15	100–200	7–17

[a] OM = Organic matter
[b] The optimum values are general recommendations for non-limited crop production (Nicholls et al., 2012)

3.3.2 Experimental design

Twelve forage entries were selected on the basis of their yield potential and suitability for winter '*in situ'* grazing or supplements. These were arranged in factorial with two N treatments in a randomised complete block design (3 replicates) (Table 3.2) with different randomization layouts at each site. Nitrogen fertiliser was applied as urea at 0 or 300 kg N/ha with split applications of 200 and 100 kg N/ha at 38 and 72 days after sowing (DAS) at Palmerston North, and 48 and 77 DAS at Tokoroa.

Table 3.2. Treatment combinations (forage entries × N treatments), species type or maturity levels, seed treatments and their effectiveness. CRM, Comparative relative maturity.

Treatment combinations	Type/maturity	Seed treatments	Pest controlled
Maize			
P8000	80 CRM	Mesurol®, Poncho® and Vitaflo ®	bird repellent, Argentine stem weevil, Black beetle, Cut worm; *Pythium, Rhizoctonia* and *Fusarium* diseases
P8805	88 CRM		
P9400	94 CRM		
Kale			
Gruner	Giant	Superstrike®	Springtails; *Pythium, Rhizoctonia, Fusarium* diseases; Molybdenum nutrient
Regal	Intermediate		
Sovereign	Intermediate		
Swede			
Triumph	Early maturity	Ultrastrike®	Springtails, Argentine stem weevil, Aphids, *Nysius* (Wheat bug); *Pythium, Rhizoctonia* and *Fusarium* diseases; Molybdenum nutrient
Clutha Gold	Medium maturity	Superstrike®	Springtails; *Pythium, Rhizoctonia, Fusarium* diseases; Molybdenum nutrient
Invitation	Late maturity	Agricote	Springtails, Argentine stem weevil, Aphids, *Nysius* (Wheat bug); *Pythium, Rhizoctonia* and *Fusarium* diseases; Molybdenum nutrient
Fodder beet			
Cerise	Grazing/Lifting	Gaucho	insects, fungal diseases
Enermax	Lifting	Thiram, hymexazol, thiamethoxam, tefluthrin	insects, seed-borne fungal diseases
Monro	Grazing	Thiram, Iprodione	fungal diseases
N treatments			
Control	0 kg N/ha		
High-N	300 kg N/ha		

3.3.3 Trial details

Forage crops were sown on 13 November 2018 at Palmerston North and 20 November 2018 at Tokoroa. Maize plots were drilled in four rows with 70 cm spacing and hand thinned to achieve the target population of 130,000 plants/ha. Maize thinning was done twice at Palmerston North (2 and 4 weeks after sowing) and once at Tokoroa (3 weeks after sowing). Fodder beet plots comprised five rows at 30 cm spacing with a target plant density of 110,000 plants/ha. The sowing rate was 220,000 seeds/ha with thinning required to achieve the target plant density. However, emergence was very close to the target density with even distribution across the plot. Consequently, thinning was not required in fodder beet at both sites. Kale and swede plots were drilled in ten rows with 15 cm spacing at 4 kg and 1.5 kg seeds/ha, respectively. All plots were 5 m long and 1.5 m wide, except for maize which was 2.8 m wide. A minimum of 2 m space was allowed between maize and other plots to avoid shading effects.

For maize and fodder beet plots, hand weeding was carried out twice, 24 and 50 DAS at Palmerston North and once at 21 DAS at Tokoroa. Versatill herbicide (Clopyralid 598 g/l ai) was applied at 1 l/ha on kale and swede plots at 48 DAS at Tokoroa and 50 DAS at Palmerston North with supplemental hand weeding.

3.3.4 Meteorological data

Meteorological data were obtained from AgResearch Grasslands, less than 1 km from the trial site at Palmerston North and the National Institute of Weather and Atmospheric Research station (NIWA) at Tokoroa (Table 3.3). The trial was irrigated between mid-January and the end of March (305 mm in total) ensuring minimal risk of moisture stress at Palmerston North. No irrigation was applied at Tokora.

Table 3.3. Mean monthly temperature (°C) and rainfall (mm) over the 2018–19 cropping season compared to the long-term mean. Long-term means: NIWA, Palmerston North, 1981–2010 and Tokoroa, 1951–1980.

	Month								
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Total
Palmerston North									
Seasonal									
Temperature (°C)	15.1	17.9	19.4	17.9	18.3	13.5	12.4	8.8	
Rain (mm)	90.8	173.0	30.8	30.0	51.6	81.0	59.5	124.6	641.3
Irrigation (mm)	-	-	105.0	120.0	80.0	-	-	-	305.0
Long-term									
Temperature (°C)	14.1	16.4	17.8	18.2	16.4	13.6	11.3	9.1	
Rain (mm)	75.1	95.6	55.1	71.1	54.7	60.1	73.5	91.9	577.2
Tokoroa									
Seasonal									
Temperature (°C)	12.1	15.0	17.2	16.7	16.4	12.0	10.8	7.6	
Rain (mm)	122.1	225.7	-	28.8	44.8	75.4	96.2	80.1	673.1
Irrigation (mm)	-	-	-	-	-	-	-	-	-
Long-term									
Temperature (°C)	13.7	15.8	17.5	17.7	15.7	12.8	9.7	7.3	
Rain (mm)	137.0	162.0	112.0	110.0	103.0	128.0	151.0	152.0	1055

3.3.5 Thermal time

As crop growth and development depend on the thermal time, thermal time was calculated for each crop to estimate the important physiological stages such as leaf appearance rate, maize silking, and harvest date of forage crops. Thermal time was calculated using the following formula with the common base temperatures of each forage crop used in NZ. The base temperatures were 0°C in fodder beet (Chakwizira et al., 2016b), 4°C in kale and swede (Adams et al., 2005; Fletcher et al., 2012) and 8°C in maize (Tsimba et al., 2013c).

$$TT = \left[\frac{(Tmax + Tmin)}{2}\right] - Tb$$

where, T_{max} = daily maximum temperature

T_{min} = daily minimum temperature

T_b = base temperature

3.3.6 Maize morphological characteristics

Maize hybrid's characteristics were recorded in the field at the Palmerston North trial but not measured at Tokoroa due to the distance (Plate 3.1). Plant height (m) was measured from the ground to the point of attachment of the tassel peduncle at anthesis (Millner et al., 2005). The height from the ground to the first cob was recorded as the cob height (cm). Both plant height and cob height were measured from 10 random plants per plot in the middle two rows. Number of leaves on the main stem were obtained from 5 plants per plot at the weekly measurement (see section 3.3.7). Days to 50% silking were monitored on the middle two rows per plot when 50% of them had produced silks.

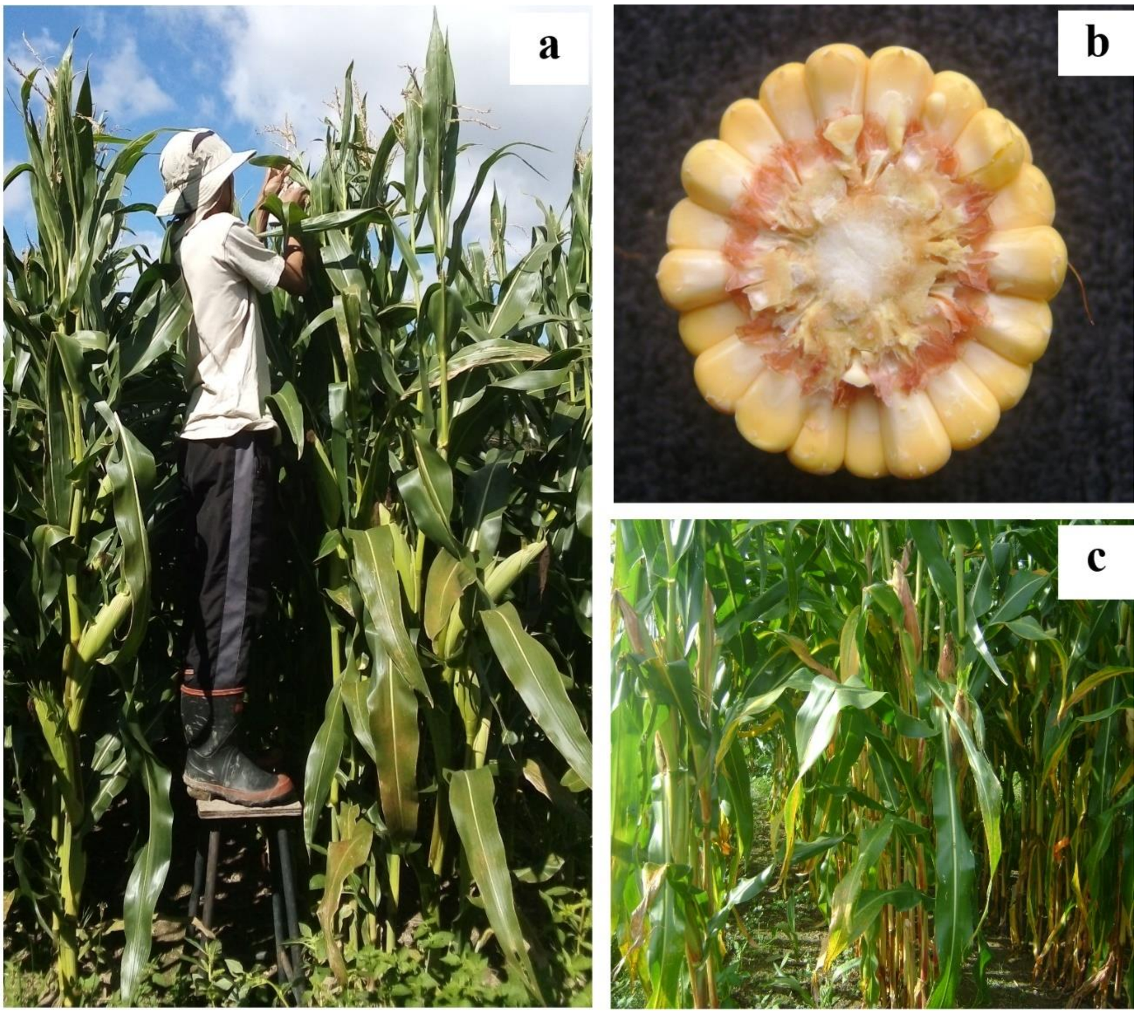


Plate 3.1. Maize plant height measurement (a), kernel milk line monitoring (b) and crop ready to harvest stage (c) at Palmerston North, New Zealand in 2018 – 2019.

3.3.7 Dry matter yield measurements

3.3.7.1 Maize

Maize yield was measured on 14 March 2019 for ‘P8000’ and ‘P8805’, and 19 March 2019 for ‘P9400’ at Palmerston North. All maize hybrids were measured on 22 March 2019 at Tokoroa. Yield measurement was done when the plant reached approximately 34% whole crop DM. Whole crop DM % was evaluated every two days from sample plants in the guard rows to ensure silage DM content of 30-38% DM (Tsimba et al., 2014; Williams, 2012) (when the kernel milk line was close to the midway of the grain, Plate 3.1) at Palmerston North but this was not feasible at Tokoroa due to the distance. Harvest samples were taken from two center rows (0.7 m × 2 rows × 2 m length = 2.8 m^2) by cutting at 10 cm above ground level. Fresh weight was recorded in the field and six representative plants from each plot were taken. Three plants were mulched using an Alko dynamic 2200 S mulcher (Plate 3.2). Approximately 200 g of mulched material was dried at 70°C to constant weight over a period exceeding 2 days for DM determination and nutrient analysis. The remaining three plants were used for yield component estimation after drying. Immediately after maize was harvested, Italian ryegrass ‘Lush’ (30 kg/ha) was sown in the maize plots at the Palmerston North trial and harvested at the same time as the fodder beet and forage brassicas.

Plate 3.2. A mulcher (Alko dynamic 2200 S) used to mulch sample maize plants (a) and mulched silage sample (b) for silage dry matter and quality analysis.

3.3.7.2 Fodder beet, kale, and swede

Dry matter yields of winter forage crops were measured on 28 June 2019 at Palmerston North and 11 June 2019 at Tokoroa. Plants were taken from 1 m row lengths, four samples per plot excluding guard rows and borders. After field weighing, three representative plants were taken, and oven-dried at 70°C to a constant weight for DM and quality analysis as well as component ratio. Nutrient analysis of maize and winter forage crops was tested only the samples from the Palmerston North trial because of incomplete fodder beet samples at Tokoroa.

3.3.8 Yield component measurements

As mentioned above, from three representative samples, maize was separated into leaf, stem, cob, and grain whereas winter forage crops were dissected into leaf and stem/bulb components (Plate 3.3). These components were also dried at 70°C to a constant weight over the exceeding 2 days. The components were statistically compared within the same crop since the plant nature was different for each forage crop.

Plate 3.3. Yield components of maize (a), kale (b), swede (c), and fodder beet (d) at Palmerston North and Tokoroa, New Zealand during the 2018 – 2019 season.

3.3.9 Feed quality test

Following DM measurement, samples were ground with a Cyclone mill (1.0 mm screen) and approximately 40 g of samples were sent to the Nutrition Laboratory, School of Food and Advanced Technology, Massey University. Samples were analysed for metabolisable energy (ME), crude protein (CP), soluble sugars and starch (SSS), acid detergent fibre (ADF) and neutral detergent fibre (NDF) using near infrared reflectance spectroscopy (NIRS). The % DM values are reported as a percentage (%) and ME value as MJ/kg DM.

3.3.10 Number of leaves per plant

Numbers of fully expanded leaves were counted weekly on five marked contiguous plants per plot non-destructively from 3 to 12 weeks after sowing (until the tasseling of maize) at the Palmerston North trial. No leaf count was carried out at Tokoroa due to the distance. Maize leaf six and 10 were tagged to use as reference points for convenient counting of leaf numbers. Similarly, the tip of the last counted (youngest) leaf was marked with paints Chakwizira et al. (2016b) and used as a reference point in counting the total number of leaves in winter forage crops (Plate 3.4). Since five plants were marked with a stick in each plot randomly, no substitution was made even if the plant was lost at a later stage. However, we found very few lost plants (negligible), and at least a minimum of four plants were kept for average in the analysis.

Plate 3.4. Leaf counts on (a) maize (tagged on leaf 6 and 10), (b) fodder beet, (c) kale and (d) swede (paint marked on the youngest leaf at each count for the reference).

3.3.11 Statistical analysis

Data were analysed using the standard general linear regression (GLM) model and correlation procedures in SAS software version 9.4 (SAS Institute Inc., Cary NC). Significant interactions and treatment means were separated using Fisher's protected least significant difference (LSD) tests when the ANOVA *F* value was significant (P≤0.05). Before the ANOVA analysis, the homogeneity of variances was tested for yield to ensure comparing across all forage entries using Bartlett's, Brown-Forsythe and Levene's tests. There was no significance of variances for yield in Bartlett's (Pr>ChiSq = 0.6351; 0.5261) and the Brown-Forsythe (Pr>F = 0.9863; 0.9647) tests while Levene's test showed significance (Pr>F =0.0144; 0.0108) at Palmerston North and Tokoroa, respectively. Therefore, we assumed variances are equal since no large deviations occurred. Orthogonal contrasts were used to test the significance of crop group means on yield, ME, and CP values at Palmerston North. A linear regression, with grouping of cultivars in the same crop type, was used to explore leaf development (leaf per plants) against the accumulated thermal time.

3.4 Results

3.4.1 Weather analysis

The growing season was quite dry except for November and December at both sites with monthly rainfall being well below the long-term mean (LTM) from mid-summer to autumn (Table 3.3). Mean monthly temperatures were generally similar between seasonal and LTM at Tokoroa while the seasonal temperature was higher than the LTM temperature at Palmerston North. High rainfall followed by a long dry spell at Tokoroa affected the establishment and vigour of fodder beet, which was poor.

3.4.2 Maize morphology

Maize hybrids differed in plant morphological characteristics, such as plant height, cob height, total leaf number, silking thermal time requirements (base 8°C) and days to 50% silking. P9400 had the greatest in plant height, cob height, total leaf number and thermal time requirement to reach silking (Table 3.4). However, N application did not affect these characteristics. In addition, no interaction occurred between hybrids and N application.

Table 3.4. Morphological characteristics of maize hybrids at Palmerston North, New Zealand during the 2018 – 2019 season.

	Plant height (m)	Cob height (cm)	Total leaf number (no.)	$SilkTT_8$[a] (°Cd)	Days to 50% silking	50% silking date
Hybrids						
P8000	2.08	101.8	15.8	669.7	68.5	20-Jan-19
P8805	1.96	103.4	17.7	698.3	71.2	22-Jan-19
P9400	2.11	116.9	18.0	726.8	74.7	26-Jan-19
LSD $_{(0.05)}$	0.09	9.6	0.7	10.0	0.9	
Nitrogen (kg N/ha)						
Omit-N (0)	2.06	107.6	17.3	699.5	71.6	
High-N (300)	2.05	107.1	17.0	696.9	71.3	
LSD $_{(0.05)}$	NS	NS	NS	NS	NS	
Interaction	NS	NS	NS	NS	NS	

[a] thermal time (base 8°C) requirements from sowing to 50% silking

NS - not significant

3.4.3 Leaf development

Crops differed in leaf appearance rate ($P < 0.001$; $R^2 = 0.99$) (Figure 3.1). Maize had the most rapid leaf appearance rate with a phyllochron of 48 and 49 °Cd/leaf under high-N and control N treatments, respectively. Fodder beet followed the second shortest phyllochron with 62 and 73°Cd/leaf with and without N applications. Kale and swede crops had the slow rate of leaf appearance with the longest phyllochron of 115 and 118°Cd/leaf under the control N treatment and 94 and 93°Cd/leaf for the N applied treatments, respectively.

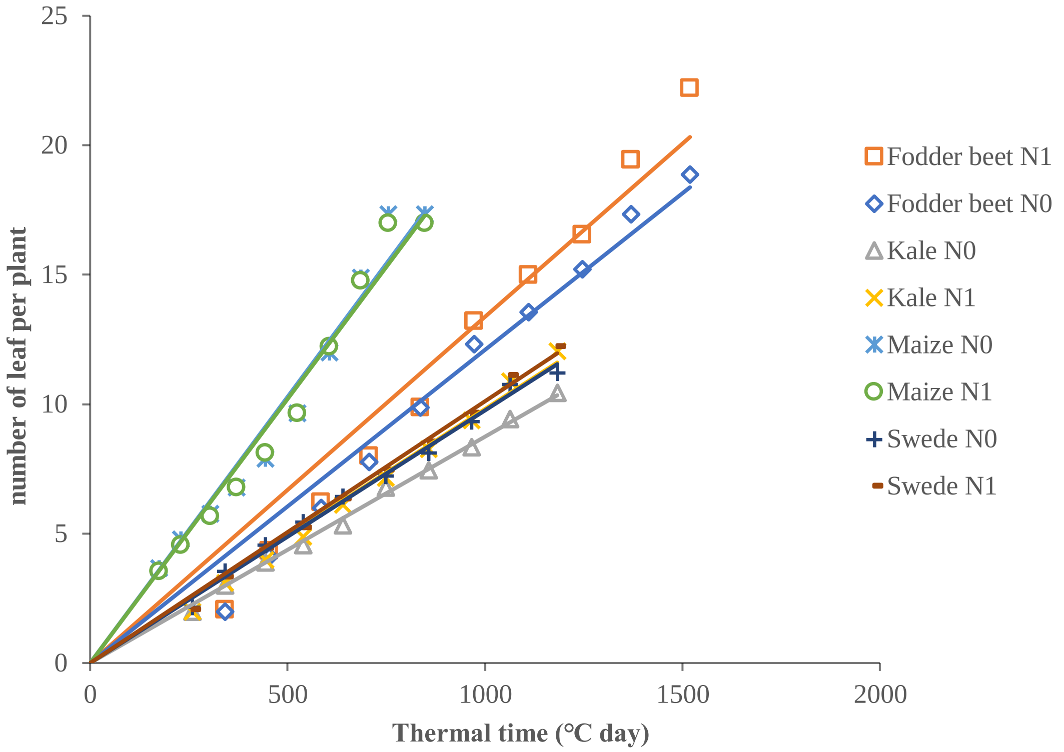


Figure 3.1. Leaf development of forage crops against accumulated thermal time under N fertiliser application at Palmerston North, New Zealand during the 2018 – 2019 season. Base temperatures (T_b) are 8°C for maize, 0°C for fodder beet, and 4°C for kale and swede. Linear regressions are y = 0.0204x and y = 0.0206x for maize, y = 0.0134x and y = 0.0121x for fodder beet, y = 0.0098x and y = 0.0087x for kale and y = 0.0101x and y = 0.0098x for swede in the order of N1 (high-N = 300 kg N/ha) and N0 (Control = 0 kg N/ha), respectively; R^2 = 0.99.

3.4.4 Yield components

There was no interaction effect between maize hybrid and nitrogen application on maize yield component contribution to yield at either site except for the grain ratio at Palmerston North (Table 3.5 and Figure 3.2). Similarly, nitrogen application only affected the leaf components at Tokoroa. Within the hybrids, maize hybrids differed in leaf components at Palmerston North while varied in grain and cob components at Tokoroa (Table 3.5).

For winter forage crops, no interaction effect was found between forage cultivars × nitrogen applications in all components of each crop (Table 3.6 and Figure 3.2). In the same way, nitrogen applications did not affect any component ratio in all crops. However, cultivar differences in plant components were found in kale and swede at Palmerston North, particularly Gruner kale had a greater percentage of the stem (83.7%), and Invitation swede showed the lower percentage of the bulb (76.3%) compared to other cultivars within the same crop (Table 3.6). No cultivars' difference in leaf and bulb components occurred in fodder beet.

Table 3.5. Effects of hybrids and N fertiliser on maize plant morphological components at Palmerston North and Tokoroa during the 2018 – 2019 season.

	Palmerston North				**Tokoroa**			
	Grain	Cob	Leaf	Stem	Grain	Cob	Leaf	Stem
	(%)				(%)			
Hybrid								
P8000	49.7	15.8	12.4	22.1	49.0	17.4	13.7	19.9
P8805	49.8	15.0	12.5	22.8	49.8	16.5	14.1	19.7
P9400	49.9	13.5	14.7	21.9	46.0	20.4	12.8	20.9
LSD (*P* = 0.05)	NS	NS	1.5	NS	2.4	2.7	NS	NS
Nitrogen (kg N/ha)								
Control (0)	49.7	13.8	13.4	23.1	47.5	17.6	14.3	20.6
High-N (300)	49.8	15.7	13.1	21.4	49.0	18.5	12.7	19.7
LSD (*P* = 0.05)	NS	NS	NS	NS	NS	NS	1.1	NS
Interaction								
Hybrid * Nitrogen	0.02	NS	NS	NS	NS	NS	NS	NS

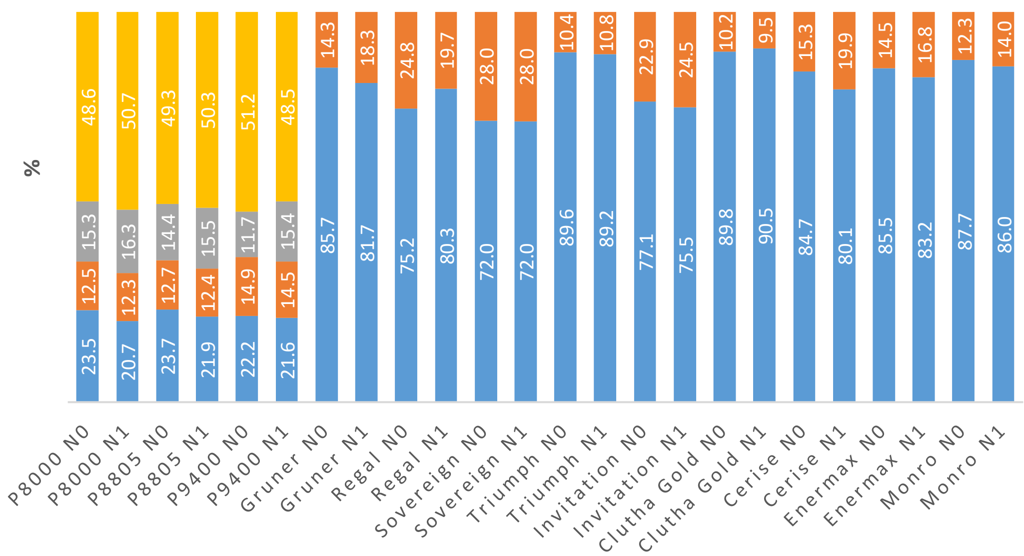
NS, not significant.

Table 3.6. Effects of cultivar and N fertiliser on plant components of kale, swede, and fodder beet at Palmerston North and Tokoroa during the 2018 – 2019 season.

	Palmerston North		**Tokoroa**	
	Kale		Kale	
	Leaf (%)	Stem (%)	Leaf (%)	Stem (%)
Cultivar				
Gruner	16.3	83.7	38.7	61.3
Regal	22.3	77.7	35.0	65.0
Sovereign	28.0	72.0	40.6	59.4
LSD (P = 0.05)	6.3	6.3	NS	NS
Nitrogen (kg N/ha)				
Control (0)	22.4	77.6	39.7	60.3
High-N (300)	22.0	78.0	36.5	63.5
LSD (P = 0.05)	NS	NS	NS	NS
Interaction				
Cultivar * Nitrogen	NS	NS	NS	NS
	Swede		Swede	
	Leaf (%)	Bulb (%)	Leaf (%)	Bulb (%)
Cultivar				
Triumph	10.6	89.4	20.5	79.5
Invitation	23.7	76.3	25.0	75.0
Clutha Gold	9.8	90.2	18.4	81.6
LSD (P = 0.05)	4.0	4.0	NS	NS
Nitrogen (kg N/ha)				
Control (0)	14.5	85.5	19.6	80.4
High-N (300)	14.9	85.1	23.0	77.0
LSD (P = 0.05)	NS	NS	NS	NS
Interaction				
Cultivar * Nitrogen	NS	NS	NS	NS
	Fodder beet		Fodder beet	
	Leaf (%)	Bulb (%)	Leaf (%)	Bulb (%)
Cultivar				
Cerise	17.6	82.4	Data was not obtained due to the poor establishment of fodder beet at Tokoroa trial.	
Enermax	15.7	84.3		
Monro	13.2	86.8		
LSD (P = 0.05)	NS	NS		
Nitrogen (kg N/ha)				
Control (0)	14.0	86.0		
High-N (300)	16.9	83.1		
LSD (P = 0.05)	NS	NS		
Interaction				
Cultivar * Nitrogen	NS	NS		

NS, not significant.

(a)



(b)

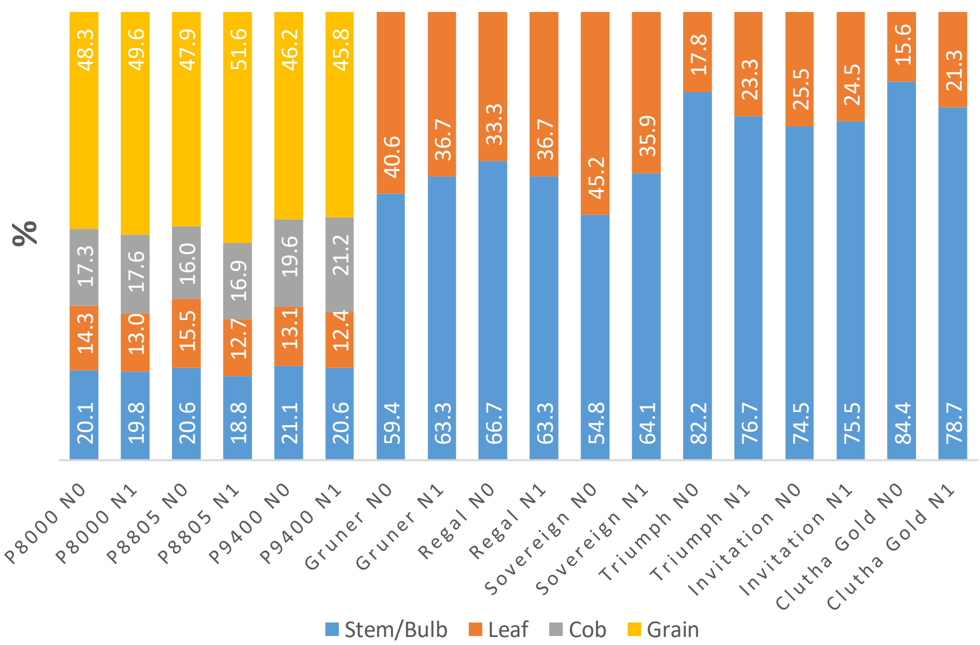


Figure 3.2. Plant component ratio of forage crops under two levels of nitrogen fertilisation at (a) Palmerston North and (b) Tokoroa. Nitrogen fertiliser: N0 (Control)= 0 kg N/ha; N1 (high-N) = 300 kg N/ha.

3.4.5 Dry matter yield

At Tokoroa, no interaction between forage entries and N treatment was observed. Dry matter yields were variable ranging from 12,733 to 22,928 kg DM/ha but no evidence was found to support statistical differences between forage treatments (Table 3.7). However, the effect of N was significant ($P<0.0009$); across all forage entries yields increased from 14,873 kg DM/ha to 21,189 kg DM/ha without and with N, respectively. Fodder beet was not harvested at Tokoroa because poor establishment and increased competition from weeds as well as the dry summer months meant most plots failed.

At Palmerston North, dry matter yields among the forage entries and N treatments differed significantly (Table 3.7). The yield ranged from 12,450 kg DM/ha for 'Invitation' swede to 30,417 kg DM/ha for 'P9400' maize hybrid. Maize hybrids produced significantly higher yields than forage brassicas or fodder beet. Maize yield averaged 29,505 kg DM/ha (Table 3.7 and Table 3.8) with an additional 2,600 kg DM/ha from the Italian ryegrass in the combined winter and summer production season. 'P9400' maize hybrid produced the maximum yield but was not different from the other hybrids (P8000 and P8805) despite the differences in maize hybrid maturities (80 CRM – 94 CRM) (Table 3.7). Differences in yield between kale (19,290 kg DM/ha) and fodder beet (20,055 kg DM/ha) groups were not significant ($P>0.05$; Table 3.8) however, differences between other group means were significant. High N (300 kg N/ha) application increased DM yield by 2,700 kg DM/ha compared with the control (0 kg N/ha) N application (Table 3.7). No interaction between forage entry and N application was observed for yield.

Table 3.7. The effect of forage entries and nitrogen fertiliser application on dry matter yield and forage quality (whole plant basis) at final harvest at Palmerston North and Tokoroa, New Zealand.

Forage crop		Dry matter yield (kg DM/ha)		Forage quality[a]				
				ME	CP	SSS	ADF	NDF
		Tokoroa	Palmerston North	(MJ/kg DM)	(%)			
Maize	P8000	17,220	29,440 (2,640)[b]	10.8	5.9	42.7	23.2	45.2
	P8805	17,421	28,657 (2,437)	10.7	5.6	42.9	24.4	44.8
	P9400	16,400	30,417 (2,753)	10.6	5.4	48.0	25.3	42.2
Kale	Gruner	18,130	21,103	9.4	7.5	26.4	29.1	36.2
	Regal	22,928	16,185	9.1	10.7	23.0	26.2	33.4
	Sovereign	15,873	20,583	8.9	9.8	23.1	28.5	36.2
Swede	Triumph	20,232	17,877	10.3	15.0	29.3	18.9	21.4
	Clutha Gold	21,341	14,035	10.1	14.5	27.9	19.6	22.2
	Invitation	12,733	12,450	10.2	15.3	25.3	19.7	21.8
Fodder beet	Cerise	-[c]	20,464	10.8	9.3	37.1	10.7	16.7
	Enermax	-	21,518	10.9	9.4	38.0	9.7	15.2
	Monro	-	18,182	10.9	11.0	37.4	11.4	17.9
	LSD (0.05)	NS[d]	5,401	0.7	1.4	5.1	2.9	3.9
Nitrogen								
Control (0 kg N/ha)		14,873	19,558	10.4	8.8	34.6	19.8	28.7
High-N (300 kg N/ha)		21,189	22,261	10.1	11.1	32.3	21.3	30.1
	LSD (0.05)	3,513	2,205	NS	0.6	2.1	1.2	NS
Pr>F	Forage Entry (En)	0.2250	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Nitrogen (N)	0.0009	0.0174	0.0591	<0.0001	0.0282	0.0129	0.0773
	En x N	0.9225	0.8131	0.0167	<0.0001	0.1249	0.0146	0.2068

[a] ME = metabolisable energy, CP = crude protein, SSS = soluble sugars and starch, ADF = acid detergent fibre, NDF = neutral detergent fibre, [b] Values in brackets are Italian ryegrass dry matter yield but excluded from data analysis, [c] Fodder beets were not able to harvest at Tokoroa, [d] NS, not significant

3.4.6 Forage quality

Samples from the Palmerston North trial were further assessed for feed quality. Forage entries × N interactions were observed for ME, CP and ADF contents. Differences between forage entries were highly significant in all quality traits assessed ($P<0.0001$; Table 3.7). Nitrogen application affected CP, SSS and ADF but did not influence ME and NDF.

3.4.6.1 Metabolisable energy

Metabolisable energy (ME) content ranged from 8.9 to 10.9 MJ/kg DM and differed significantly among the forage entries (Table 3.7). Maximum ME values (10.9 MJ/kg DM) were observed in 'Enermax' and 'Monro' fodder beets but were not different from 'Cerise', maize hybrids, or 'Triumph' swede. The kale cultivars had low ME values (8.9–9.4 MJ/kg DM) especially 'Sovereign'. Crop group means for ME were generally significantly different, the exception being maize (10.7 MJ/kg DM) versus fodder beet (10.8 MJ/kg DM) (Table 3.8).

3.4.6.2 Crude protein

The crude protein content of most trial entries was lower than the maintenance level required by dairy cows during wintering (less than 12%) (National Research Council, 2001), except for swedes which had CP ranging from 14.5–15.3% (Table 3.7). The lowest CP occurred in the maize hybrids (5.4–5.9%). The CP content was likely to vary within the kale and fodder beet cultivars (Table 3.7), but the average CP contents between kale (9.4%) and fodder beet (9.9%) were not significant (Table 3.8). The high N treatment also increased the CP content (11.1%) compared to the control (8.8%) ($P<0.0001$; Table 3.7).

3.4.6.3 Soluble sugars and starch

The highest SSS value was observed in maize ‘P9400’ (48.0%) (Table 3.7). Fodder beet entries had intermediate SSS levels while forage brassicas were generally low. In comparing the means overall entries, the N application caused a slight decrease in SSS (32.3%) when compared to the control (34.6%) (P=0.0282; Table 3.7).

3.4.6.4 Fibre content

Fibre content was lowest (ADF 9.7–11.4% and NDF 15.2–17.9%) in fodder beet. Conversely, ADF content was highest in the kale (26.2–29.1%) while NDF was highest for maize (42.2–45.2%) (Table 3.7).

Table 3.8. Orthogonal contrast between forage crop group means. Cultivars within the same crop and N levels were pooled for crop group mean analysis. *P<0.05, **P<0.01, ***P<0.001, [NS] not significant.

	DM Yield[a] (kg DM/ha)	ME[b] (MJ/kg DM)	CP[c] (%)
<u>Group mean</u>			
Maize	29,505	10.7	5.6
Kale	19,290	9.1	9.4
Swede	14,787	10.2	14.9
Fodder beet	20,055	10.8	9.9
<u>Contrast analysis</u>			
Maize vs kale	***	***	***
Maize vs swede	***	*	***
Maize vs fodder beet	***	NS	***
Kale vs swede	**	***	***
Kale vs fodder beet	NS	***	NS
Swede vs fodder beet	**	**	***

[a]DM yield = dry matter yield, [b]ME = metabolisable energy, [c]CP = crude protein

3.4.7 Correlation analysis

Correlation analysis was used to examine the association between yield and quality data from the Palmerston North trial. Dry matter yield was positively correlated with SSS (r = 0.58) and NDF (r = 0.56) but negatively correlated with CP (r = -0.61, P<0.001; Table 3.9). Similarly, ME was positively and strongly correlated with SSS (r = 0.79, P<0.001) while negatively correlated with CP (r = -0.25, P<0.05), ADF (r = -0.63, P<0.001) and NDF (r = -0.25, P<0.05). Crude protein had a moderate, negative correlation with SSS (r = -0.61, P<0.001) and NDF (r = -0.57, P<0.001). Acid detergent fibre and NDF were strongly and positively correlated (r = 0.83, P<0.001).

Table 3.9. Simple correlation coefficient between dry matter yield and forage qualities at final harvest at Palmerston North, New Zealand. *P<0.05, **P<0.01, ***P<0.001, NS not significant.

	DM Yield[a] (kg DM/ha)	ME[b] (MJ/kg DM)	CP[c] (%)	SSS[d] (%)	ADF[e] (%)	NDF[f] (%)
DM Yield	1					
ME	0.22	1				
CP	-0.61***	-0.25*	1			
SSS	0.58***	0.79***	-0.61***	1		
ADF	0.21	-0.63***	-0.19	-0.32**	1	
NDF	0.56***	-0.25*	-0.57***	0.15	0.83***	1

[a]DM yield = dry matter yield, [b]ME = metabolisable energy, [c]CP = crude protein, [d]SSS = soluble sugars and starch, [e]ADF = acid detergent fibre, [f]NDF = neutral detergent fibre

When plant N content was plotted against the SSS:CP ratio, the relationship was negative curvilinear (Figure 3.3). The average SSS:CP ratio of maize and fodder beet was greater than 3 which is the threshold to suggest a feed for minimising urinary N excretion (Dalley et al., 2017; de Ruiter et al., 2019). All brassica treatments showed less than 3 in the average SSS:CP ratio.

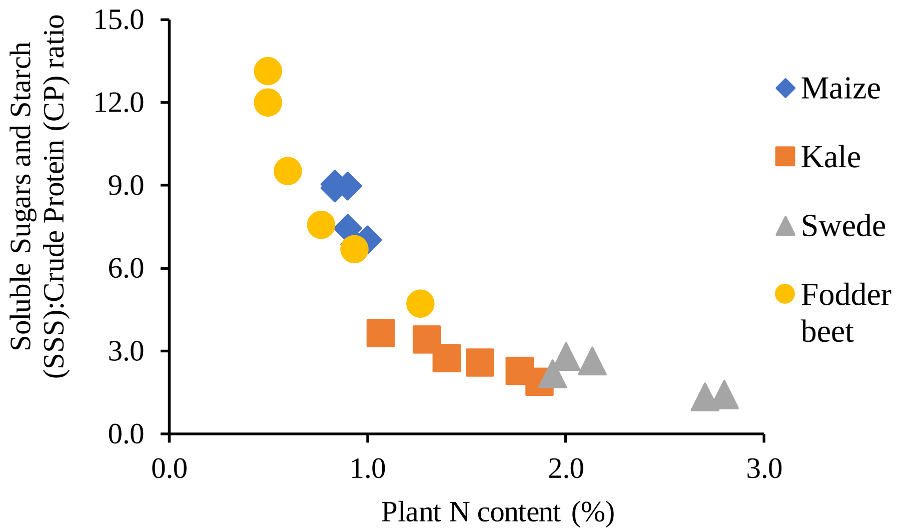


Figure 3.3. The relationship between plant N content and the soluble sugars + starch and crude protein ratio (SSS:CP).

3.5 Discussion

This study provided an initial assessment of yield and forage qualities of a wide range of forage entries in response to N fertiliser applications under non-limitations of water at Palmerston North and rain-fed conditions at Tokoroa. The results were used to select the cultivars for succeeding experiments across a greater range of environments.

3.5.1 Maize morphology and leaf development of forage crops

The differences in maize morphological characteristics reflected the comparative relative maturity (CRM) of maize hybrids. The longer CRM hybrids had higher in plant height, cob height and total leaf number. Likewise, the late maturing hybrids required a greater thermal requirement for the silking time (Table 3.4). The difference in plant character in maize hybrids highlighted the need to manage the harvest timing and the treatments arrangement for subsequent trials.

The leaf appearance rate of 48/49, 62/73, 94/115 and 93/118°Cd/leaf (with/without N applications) for mazie, fodder beet, kale and swede are generally consistent with the previous research (Chakwizira et al., 2016b; Tsimba et al., 2013c; Wilson et al., 2004). However, kale and swede's phyllochron are slightly longer compared to the results of Fletcher et al. (2012). This is because the leaf counts stopped in late February in our study when all maize leaves had emerged completely rather than being measured until the harvest of winter forage crops. In general, the faster in leaf appearance means more rapid closure of the canopy, allowing to receipt of greater radiation interception. Maize is faster in canopy development, primarily due to a shorter phyllochron length. Time to canopy closure also depends on the spacing and individual leaf area of specific crop. For example, kale and swede reached canopy closure faster than fodder beet (visual observation) due to a lower spacing (15 cm) although fodder beet had shorter phyllochron and rapid leaf appearance rate. The rapid leaf development can also supress weeds at the earlier growth stage along with the rapid canopy closure (visual observation).

3.5.2 Yield components

Plant components contributed to the total yield and consequently, they were useful parameters to select the cultivar of each forage crop for further experiments. About half of the total components were grain in all maize hybrids (Table 3.5 and Figure 3.2), which is similar to the previous research in NZ (Millner et al., 2005; Tsimba et al., 2013a). For maize, the components difference was not observed except less grain component in P9400 at Tokoroa, which may be due to the same harvest time for all hybrids at Tokoroa. This indicated allocation of maize hybrids should be adjusted in subsequent trials if all hybrids are intended to be harvested at the same time. For winter forage crops, components differences in kale and swede occurred at Palmerston North but not at Tokoroa. This indicated that irrigation may influence these components of kale and swede crops since N application did not affect plant components at both sites (Table 3.6). In addition, the higher stem percentage in 'Gruner' kale and lower bulb components in 'Invitation' swede reflected the total yield. Taking account of this, irrigation management should be considered for further research.

3.5.3 Dry matter yield

At Tokoroa, there were no yield differences among forage treatments but there was a response to N application. Compared with the Palmerston North trial, kale and swede yields were similar at both sites whereas maize yields were considerably lower at Tokoroa (29,500 vs 17,000 kg DM/ha on average) (Table 3.7). This is partly due to the very low rainfall in January and February at Tokoroa (Table 3.3) which may pose moisture stress and probably coincide with the time of silking and grain development of maize. On the other hand, it indicated that maize responded to irrigation more than other forage crops at Palmerston North.

At Palmerston North, although yields were increased by N application, there was no interaction between N application and forage treatment, indicating that all crops responded in the same way. Maize yields of 28,657–30,417 kg DM/ha were generally consistent with the previous reports in NZ (Chakwizira et al., 2017b; Densley et al., 2006; Johnstone et al., 2010; Minnée et al., 2009; Tsimba et al., 2014). Despite being a shorter season crop than fodder beet or forage brassicas, maize (C_4 species) was more productive because of its greater conversion efficiency of solar radiation to crop biomass (Minnée et al., 2009). Maize also responded to irrigation, approximately 30% increase in yield in the literature with fully irrigation in a similar climate in Australia and NZ (Islam et al., 2012; Teixeira et al., 2014).

Kale and swede yields were within the range suggested by NZ companies (Anon., 2019) and slightly higher than yields reported by previous studies conducted in southern locations of the country (Chakwizira et al., 2012; Chakwizira et al., 2013a; Westwood et al., 2014). Total rainfall and average temperature during the growing season were higher in this study (641 mm: ~15.4°C) than the above studies (about 270-540 mm: ~12.5°C), which may account for the increased yields of kale and swede.

Fodder beet yields were generally low (20,055 kg DM/ha mean) compared with the potential yield of >30 t/ha (Matthew et al., 2011). However, Matthew et al. (2011) found yield variation from 19-35 t DM/ha at two farm sites in Central Hawke's Bay. Fodder beet is slow to establish (30-60 DAS), so probably intercepted less light early in the season compared with other crops in the trial (Matthew et al., 2011), reducing yield. Khaembah et al. (2019) reported an 18% yield reduction due to limited radiation interception between October- and November-sown fodder beet crops. On the other hand, fodder beet yields in this study were similar to those obtained by Milne et al. (2014), who reported that both cultivar and sowing date influenced yield. Likewise, fodder beet yields in this study meet a commercial target of 19 t DM/ha (Judson et al., 2016).

3.5.4 Feed quality

Among feed quality traits (Table 3.7), ME values were within the recommended ranges for all forage entries (9.5–11.0 MJ/kg DM) except kale. Maize ME contents were consistent with previous studies in Manawatu (Millner et al., 2005). However, kale ME contents (8.9–9.4 MJ/kg DM) were surprisingly low in this study compared with previous reports; 11.4 MJ/kg DM (Westwood et al., 2014) and ~12.1 MJ/kg DM (Cheng et al., 2018). Poor ME content in kale treatments could be related to lower SSS and higher ADF contents (Table 3.7); ADF is negatively correlated and SSS is positively correlated with ME (Table 3.9).

There was a negative correlation between CP and ME content in this research, contrary to the results of Millner et al. (2011) who tested sorghum, sudan-grass and pearl millet in Manawatu. However, the relationship between CP and DM yield was consistent with the findings of the same authors. The low CP observed in the maize, kale and fodder beet entries would limit their ability to meet the protein requirements of non-lactating cows in winter (Chakwizira et al., 2015b; Dalley et al., 2017; Kolver et al., 2001). The low CP content is a result of the protein dilution effect caused by an increase in the rate of accumulation of dry mass other than the accumulation of protein (Fletcher & Chakwizira, 2012; Zhao et al., 2020). It may also be a consequence of the lower concentrations of CP in the most important yield components, such as bulbs in fodder beet and stems in kale (contributed ~80% of total DM) (Chakwizira et al., 2014a, 2015b; Chakwizira et al., 2018).

The average SSS contents of maize and kale were similar to findings of previous studies (Dalley et al., 2017; Westwood et al., 2014) but that of swede and fodder beet entries were lower than the previous studies in NZ (Chakwizira et al., 2014a; Dalley et al., 2017; Dalley et al., 2020b). The higher SSS contents were positively correlated with ME and DM yield, and can be used to balance nutrient requirements for dairy cows in early to mid-lactation (Kolver et al., 2001).

Forage fibre content is important for rumen function and maintaining milkfat percentage at mid- and late-lactation (Kolver et al., 2001). Average ADF and NDF values of kale and maize were within the range reported in previous research (Cheng et al., 2018; Dalley et al., 2017; Westwood et al., 2014). The values of ADF (<20%) and NDF (<28%) in swede and fodder beet were within the range reported by Dalley et al. (2017) but seemed to be poor for rumen activity (Gibbs, 2014).

3.5.5 Feed versus environmental benefits

Crude protein content increased marginally with the application of N fertiliser. This is contrary to the result of Chakwizira et al. (2014a). However, the same result was found in forage brassicas and summer forage crops at different N doses in Australia where annual rainfall was similar to this study (Jacobs & Ward, 2011). The CP values achieved in this study were generally low despite high rates of N fertiliser use (Table 3.7 and Figure 3.3).

The SSS:CP ratio was high in maize (6.9–9.0) but was quite varied in fodder beet (4.7–13.1) (Figure 3.3), similar to previous research (Dalley et al., 2020b). Generally, CP<12% and SSS>30% or SSS:CP ratio >3 is regarded as adequate for minimising the risk of nitrate leaching from deposited urine (Dalley et al., 2017; de Ruiter et al., 2019). Perennial ryegrass-white clover, the main feed for cows in NZ, has high CP content (up to 30%) (Dalley & Gardner, 2012; Dalley & Geddes, 2012; Waghorn et al., 2007), so low protein supplementary feed is desirable to reduce cow urine N. Fodder beet and maize were likely to be the better forage options for reducing N leaching compared to the brassica crops while feed composition must meet animals' nutrition requirements. However, fodder beet is considered a poor supplement for lactating dairy cows due to high acidosis risk and low milk response when intake exceeds 27% of daily dry matter intake (Fleming et al., 2020a).

3.5.6 Selection of cultivars for further experiments

The superior cultivars in yield and quality traits were further selected to minimise the number of treatments in a manageable condition under multi-environment experiments (considering 4 or 5 trials) across the lower North Island during the next season (2019 – 2020).

All maize hybrids were chosen with the intension of seeing yield differences between the early and late maturing hybrids under the different environments. However, the treatment arrangement for maize hybrids will be considered in each trial in the next season experiments since there were hybrids's differences in morphological characteristics (Table 3.4) and less grain component in P9400 at Tokoroa due to the same harvest time (Table 3.5).

For winter forage crops, one cultivar from each crop was further selected based on yield and quality as well as the resistance to diseases during the cropping season. For example, 'Gruner' kale was selected for further experiments due to its high yield and quality but also its performance in lodging and black rot disease (*Xanthomonas campestris* pv. *campestris*) resistance compared to 'Regal' and 'Sovereign' kales under 0 and 300 kg N/ha fertiliser applications (Table 3.10 and Figure 3.4). Likewise, the 'Triumph' swede cultivar was chosen for further research due to its yield on both sites (Table 3.7) and quality attributes while clubroot disease (*Plasmodiophora brassicae*) incidence scores were not different in three swede cultivars (Table 3.11 and Figure 3.5). No disease occurred on fodder beets. It should be noted that all fodder beet cultivars were the same in yield and quality as well as their component ratio, so it was considered reasonable to choose any cultivars for further experiments. Since the highest yield, higher ME and lower CP are the priority, Enermax fodder beet was chosen for further experiments.

Table 3.10. Mean lodging and black rot disease (*Xanthomonas campestris* pv. *campestris*) incidence scores of kale cultivars at Palmerston North, New Zealand. NS, not significant.

	Score	
	Lodging[a]	**black rot disease**[b]
Kale cultivar		
Gruner	2.33	0.67
Regal	2.83	1.50
Sovereign	3.00	1.50
LSD **(0.05)**	NS	0.73
Nitrogen (N)		
0 kg N/ha	1.89	0.89
300 kg N/ha	3.56	1.56
LSD **(0.05)**	1.03	0.59
Pr>F		
Cultivar	0.4947	0.0447
Nitrogen	0.0047	0.0319
Cultivar x N	0.0102	0.0141

[a] visual assessment of lodged plants per plot (1 = ≤10% lodging, 10 = 100% lodging)
[b] visual assessment of disease incidence (0 = Absent, 5 = Very high)

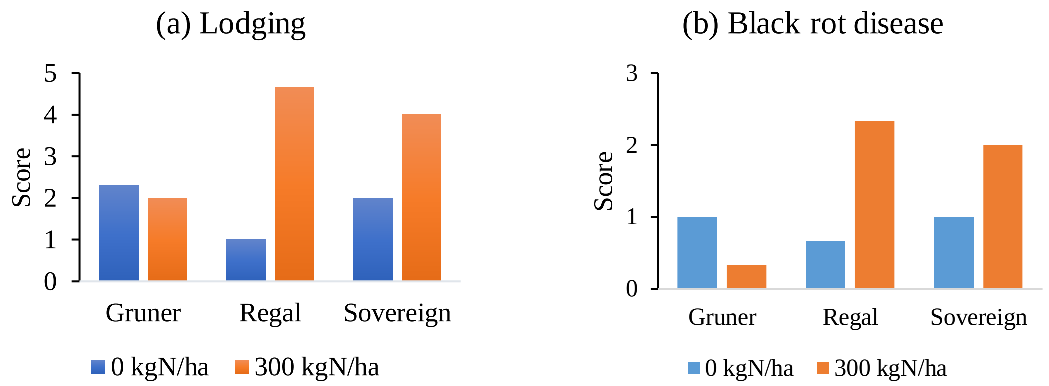


Figure 3.4. Lodging incidence scores (a) based on visual assessment of lodged plants per plot (1 = ≤10% lodging, 10 = 100% lodging) and black rot disease (*Xanthomonas campestris* pv. *campestris*) incidence scores (b) (0 = Absent, 5 = Very high) of kale cultivars under 0 and 300 kg N/ha fertiliser applications at Palmerston North, New Zealand during the 2018 – 2019 season.

Table 3.11. Mean clubroot disease (*Plasmodiophora brassicae*) incidence scores of swede cultivars at Palmerston North, New Zealand. NS, not significant.

	Clubroot disease score[a]
Swede cultivar	
Triumph	2.67
Clutha Gold	2.83
Invitation	2.83
LSD $_{(0.05)}$	NS
Nitrogen (N)	
0 kg N/ha	3.00
300 kg N/ha	2.56
LSD $_{(0.05)}$	NS
Pr>F	
Cultivar	0.9658
Nitrogen	0.4717
Cultivar x N	0.5359

[a] visual assessment of disease incidence scores (0 = Absent, 5 = Very high)

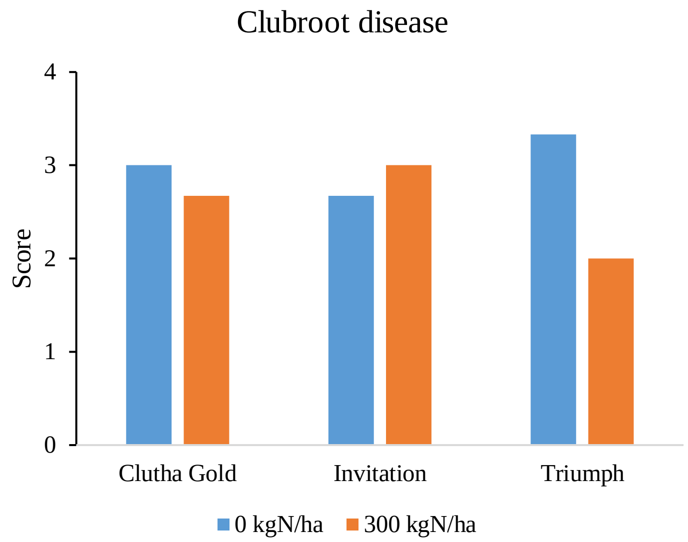


Figure 3.5. Clubroot disease (*Plasmodiophora brassicae*) incidence scores (0 = Absent, 5 = Very high) of swede cultivars under 0 and 300 kg N/ha fertiliser applications at Palmerston North, New Zealand during the 2018 – 2019 season.

3.6 Conclusion

Maize yields were higher than that of winter forage crops at Palmerston North but similar to kale and swede yields at Tokoroa. Nitrogen application affected yields at both sites but did not influence plant components. Maize yields at Palmerston North were higher than at Tokoroa, possibly due to an irrigation. Metabolisable energy content was good in all forage entries except kale. The crude protein content was quite low in maize and fodder beet, indicating the potential for lower N leaching with high proportions of these feeds in animal diet. Nitrogen application affected some quality traits (CP, SSS and ADF). The threshold of SSS:CP ratio (>3) showed maize and fodder beet had high potential to reduce urinary N excretion. The results suggest maize as the best option on the basis of yield and overall nutritive value under non-limiting soil moisture for growth. For further experiments, all maize hybrids, 'Gruner' kale, 'Triumph' swede and 'Enermax' fodder beet were selected based on yield and quality as well as their resistance to diseases or lodging.

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Chapter 4 Yield and feed quality of forage crops in a range of environments in New Zealand

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Chapter 4 was intended to publish in peer review journals.

4.1 Abstract

Intensive grazing of winter forage crops poses significant environmental risks such as nitrate leaching and soil quality deterioration in New Zealand, requiring a viable alternative cropping option. We proposed maize silage (referred to as 'maize' hereafter) could be an alternative crop because of its low N content and convenience in a cut and carry system. Along with the potential to minimise environmental risks (e.g. nitrate leaching), research needs to demonstrate that the alternative crop has the competitive yield and feed quality to meet animal requirements. We compared maize and winter forage crops (WFC) – kale, swede, and fodder beet to investigate the dry matter yield and feed quality in the lower North Island areas. Three experiments were located at Massey University (MU) and one experiment at Kiwitea, both locations are in the Manawatu region. Overall, maize (10,940 – 26,792 kg DM/ha) yielded more than kale (7,016 – 19,278 kg DM/ha), swede (4,579 – 12,233 kg DM/ha), and fodder beet (7,020 – 13,581 kg DM/ha) across the experiments. Maize produced higher yields at the MU site while similar yield to forage brassicas at Kiwitea. Irrigation increased yields by 29% to 63% depending on the forage species. Italian ryegrass planted after maize produced a further 1,209 – 2,761 kg DM/ha. All crops produced forage with good metabolisable energy (ME) values at both sites (>11 MJ ME/kg DM). The crude protein (CP) content of maize (5.7 – 9.2%) and fodder beet (7.6 – 11.2%) were low compared with forage brassicas (8.3 – 16.6% in kale and 11.4 – 18.2% in swede). Soluble sugars and starch (SSS) were highest in fodder beet, followed by maize. Acid detergent fibre (ADF) was generally lower than the optimum level (<21%) in all forage crops tested. Neutral detergent fibre (NDF) was the highest in maize but lower than the recommended level (33%) in all WFC. Kale had lower ME and CP contents while increasing fibre contents (ADF and NDF) under irrigation, in contrast to maize. Swede has the greatest site differences in SSS and fibre

contents. The results showed that maize is able to produce higher yields with adequate feed quality for maintenance feeding of cattle compared with the WFC at Massey University.

keywords: maize silage, kale, swede, fodder beet, supplementary forage crops, forage brassicas, dry matter yield, forage quality, irrigation, leaf area index, plant components

4.2 Introduction

Dairy farming in New Zealand (NZ) is primarily based on perennial ryegrass/white clover pastures (Macdonald et al., 2010; Moot et al., 2009) but there has been an increase in home-grown supplementary feed crops to fill in during periods of feed shortage (Barry, 2013; Dalley et al., 2020a; Fletcher et al., 2012; Wilson et al., 2006). Consequently, the use of supplementary forage crops is becoming a significant part of the NZ dairy sector to provide sufficient feed to meet animal requirements and ensure animal welfare. Despite this importance, intensive grazing of winter forage crops (e.g. kale, swede, and fodder beet) are a significant concern for water quality deterioration via nitrate leaching (Beukes et al., 2011a). This is resulting in increased scrutiny from the NZ public (Dalley, 2011; Dalley et al., 2017) due to the negative effects on the environment if grazed over the winter (Ministry for Primary Industries, 2021).

Wintering on forage crops can cause many negative effects but the greatest concern is nitrogen (N) leaching primarily through high urinary N loading (Castillo et al., 2000; Dalley et al., 2017) resulting from high stocking densities (1000 – 2000 cows per ha) (Monaghan et al., 2017) particularly under heavy winter rainfall (Edwards et al., 2017; Malcolm et al., 2017). Wintering cows on grazed paddocks can also increase soil compaction, and soil bulk density (Chamen et al., 2015; Drewry et al., 2021; Laurenson & Houlbrooke, 2016), and leave a large crop residue load in paddocks after grazing due to lower crop utilisation (DairyNZ, 2013; Rugoho, 2013; Thompson et al., 2012). However, higher crop utilisation may occur depending on the season, cultivar, and soil type (Edwards et al., 2014b). A potential alternative to WFC for many areas is maize. Maize has high yield potential (18 – 25 t DM/ha), a convenient cut and carry production system, practical storage options and good potential for reducing urinary N excretion in mixed diets (Dalley et al., 2020b; Gregorini et al., 2016). Furthermore, maize is also potentially adaptable to the future climate scenario in NZ through an expansion of the areas suitable for growing maize due to warmer temperatures (Dynes et al., 2010b; Teixeira et al., 2012).

A comparison of the yield and feed quality of maize with traditional winter forage crops in a range of environments is required because of the importance of these attributes for farmers (Clark et al., 2007). Moreover, there is little research on a side-by-side comparison of both maize and WFC in NZ or elsewhere compared with the extensive experimentation that has been done on single or two crops (Chakwizira et al., 2014a; Chakwizira et al., 2011a; Chakwizira et al., 2013b; Dalley et al., 2020b; Fletcher & Chakwizira, 2012; Gowers et al., 2006; Teuber et al., 2020; Tsimba et al., 2014; Villalobos & Brummer, 2015; Watt et al., 2019).

Irrigation has a significant effect on the yield and feed qualities of forage crops in NZ (Clark et al., 2001), especially in regions where summer rainfall is insufficient and unpredictable (Chakwizira et al., 2014b). The effect of irrigation was highlighted on the individual forage crops. This includes brassica crops and fodder beet (Chakwizira et al., 2014b; Chakwizira et al., 2013a) as well as maize (Teixeira et al., 2014). Not only does water stress reduce the yield of forage crops (maize and sorghum), it also decreases digestibility due to increased ADF and NDF (Nematpour et al., 2021). Likewise, Gallo et al. (2014) found that a reduction in irrigation not only affected crop yield but also the chemical composition and nutrition of forage maize.

While research exists on the yield and quality of some crops, there is still a knowledge gap in how crop management or crop type influences the yield and quality under a range of environments. We established trials with maize, kale, swede, and fodder beet crops at Massey University (MU) and Kiwitea. The aim of the research was to compare forage crops under a range of management regimes. The objectives were to compare yield and feed quality attributes of maize, kale, swede, and fodder beet crops, and to identify any interactions between crop species and environment for yield and feed quality traits.

4.3 Materials and Methods

4.3.1 Experimental sites

Four field trials were established: three at the Pasture and Crop Research Unit, MU, Palmerston North (40° 22′ 53″ S, 175° 36′ 22″ E; 18 m asl) and one on a sheep and beef farm at Kiwitea (40° 05' 51.6" S 175°45' 05.2" E; 380 m asl). The Kiwitea site was selected because the higher altitude means that it has lower temperatures than the MU site and so less suited to production of maize. Two of the trials at MU were irrigated, referred to as MU irrigated and MU non-irrigated trials. The remaining trials at MU and Kiwitea were established on the same day but at a later date and are referred to as MU late and Kiwitea late trials. The purpose of the late planting date was to simulate typical farmer practice in the region where forage crops such as swedes and kale are planted in late spring or early summer when feed deficits occur.

The soil at the MU site is a well-drained Manawatu fine sandy loam (Weathered Fluvial Recent soil). At the Kiwitea site, the soil is Kiwitea silt loam, a moderately well-drained mafic brown soil (Argillic-fragic Perch-gley Pallic soil) (Hewitt et al., 2021; Landcare Research, 2021; NZ soils, 2021). Composite soil samples (20 cores) were taken from each site for soil nutrient analyses to ensure adequate soil fertility for the initial crop establishment. The soil nutrient properties before the experiment along with the optimum nutrient values are given in Table 4.1.

Table 4.1. Soil characteristics before the experiment (0-15 cm depth) at Massey University and Kiwitea, New Zealand in 2019 – 2020.

Site	**pH**	**Olsen P**	**K**	**Ca**	**Mg**	**Na**	**Mineral N**	**OM**[a]
		---------------------------mg/kg---------------------------					**kg/ha**	**%**
Massey	5.3	60	140	875	120	15	99	3.7
Kiwitea	5.7	24	160	875	90	25	160	5.7
Optimum[b]	5.8-6.2	20-30	120-200	500-1250	≥50	10-15	100-200	7-17

[a] OM = Organic matter; [b]The optimum values are general recommendations for non-limited crop production (Nicholls et al., 2012)

4.3.2 Treatments

All experiments were arranged in a randomised complete block (RCB) design with four replications, using a different randomisation layout for each experiment. Each experiment consisted of five crop treatments: three WFC and two maize hybrids (either P8805 and P8000 or P8805 and P9400) (Table 4.2). Considering different sowing dates, MU irrigated- and MU non-irrigated trials received maize hybrids P8805 and P9400 whereas MU late and Kiwitea late trials received maize hybrids P8000 and P8805 to ensure the practical harvesting maize hybrids at the same time (see Chapter 3 requiring arranging the harvest time due to hybrids' maturity). Italian ryegrass (cv. Lush) was sown after maize harvest at MU irrigated and MU non-irrigated trials. The individual plot size was 22.4 m^2 (2.8 x 8 m) for maize plots and 12 m^2 (1.5 x 8 m) for WFC. A minimum of 2 m space was allowed between maize and other plots to avoid shading in all trials. Crop types, established seed rates, and plant spacing are detailed in Table 4.2. Plots consisted of four rows of maize, five rows of fodder beet, and ten rows each for kale and swedes.

Table 4.2. Forage crops treatment details used in experiments at Massey University and Kiwitea, New Zealand during the 2019 – 2020 season.

Crop	Description	Plot size (m^2)	Established seeding rate (seeds/ha)	Row spacing (drilled)	Target plants/m^2
Maize					
P8000	80 CRM[a]	22.4	240000	70 cm	
P8805	88 CRM	22.4	240000	70 cm	12
P9400	94 CRM	22.4	240000	70 cm	
Italian ryegrass[b]					
Lush AR37	Annual	22.4	30 kg/ha	broadcast	-
Winter forage crops (WFC)					
Gruner kale	Giant	12	4 kg/ha	15 cm	45
Triumph swede	Early maturity	12	1.5 kg/ha	15 cm	45
Enermax fodder beet	Lift/grazing	12	220000	30 cm	11

[a] CRM-comparative relative maturity

[b] Sow Italian ryegrass after the maize harvest

4.3.3 Crop management

Maize and fodder beet plots were sown at a high rate and thinned after emergence to achieve the target population (Table 4.2). Maize was thinned at 3-4 weeks after sowing in all experiments (Table 4.3). Other than removing some seedling clusters, fodder beet plots did not require much thinning because the plant population was close to the target. At the final harvest, the harvested plant population (Table 4.5) was counted for all crops to assess any potential impact of population variation on yield. To control weeds, hoeing and hand weeding were mainly done in maize and fodder beet crops while Versatill herbicide (Clopyralid 598 g/l ai) was applied to kale and swede plots at a rate of 1 l/ha. The details of weed controls were shown in Table 4.3.

4.3.4 Fertiliser application

The same amount of urea fertiliser (200 kg N/ha) was applied to all trials. From the first season trials, kale lodging and disease incidence were greater in high N plots compared to control N plots (Figure 3.4). This indicates a medium rate of N fertiliser (200 kg N/ha) may have been appropriate to maximise yields while focusing on irrigation and site differences in the second season. The side dressing of fertiliser was done when the soil had enough moisture to minimise N loss through volatilization, so the time of application differed in each experiment. The first split application of urea was applied just after the first weeding (approximately 4-6 weeks after planting). The second and third splits of urea were applied after the second supplemental hand weeding, coinciding approximately with maize silking time and the beginning of grain filling. The detailed split dosage and time of application were given in Table 4.3.

Table 4.3. Crop management details of experiments grown at Massey University and Kiwitea sites of New Zealand during the 2019-2020 season.

Crop details	**Experimental sites**			
	MU irrigated	**MUnon-irrigated**	**MU late**	**Kiwitea late**
Management	irrigated	non-irrigated	late sowing, rainfed	late sowing, rainfed
Sowing date	1 Nov 2019	1 Nov 2019	29 Nov 2019	29 Nov 2019
Thinning of maize	2 Dec 2019	3 Dec 2019	16 Dec 2019	22 Dec 2019
Irrigation (mid-January to late March)	425 mm	-	-	-
Weed control				
Hand weeding (maize and fodder beet)	4 Dec 2019	5 Dec 2019	17 Dec 2019	22 Dec 2019
Versatill (Clopyralid 598 g/l ai) spray at 1 l/ha on kale and swede	6 Dec 2019	6 Dec 2019	21 Dec 2019	9 Jan 2020 2 Feb 2020[a]
Supplemental hand weeding of all crops	7-14 Dec 2019	7-14 Dec 2019	-[b]	12 Jan 2020[c]
Fertiliser (kg N/ha) (Urea 46%)				
1st application	100 (10 Dec 2019)	100 (10 Dec 2019)	50 (17 Dec 2019)	50 (22 Dec 2019)
2nd application	50 (22 Jan 2020)	50 (22 Jan 2020)	100 (22 Jan 2020)	100 (28 Jan 2020)
3rd application	50 (30 Jan 2020)	50 (30 Jan 2020)	50 (5 Feb 2020)	50 (17 Feb 2020)
Harvest date (Duration days)				
maize	24 Mar 2020 (144)	24 Mar 2020 (144)	1 May 2020 (154)	30 Apr 2020 (153)
WFC	27 Jul 2020 (269)	28 Jul 2020 (270)	28 Jul 2020 (242)	25 Jul 2020 (239)
Italian ryegrass[d]	31 Jul 2020 (129)	31 Jul 2020 (129)	-	-

[a] Herbicide sprays on winter forage crops for the second time due to the weed dominance at the Kiwitea site

[b] Supplemental weeding is not necessary at MU late trial

[c] Hand weeding was mainly done on maize silage and fodder beet

[d] Italian ryegrass was sown immediately after maize harvest at MU irrigated and non-irrigated trials but not in other trials

4.3.5 Meteorological data

Daily rainfall and temperature for the MU site were obtained from the AgResearch Grasslands, Palmerston North, less than 1 km from the trial site. Rainfall data for Kiwitea was obtained from the National Institute of Water and Atmospheric Research automated weather station (NIWA) situated near Waituna (11 km distance). At the Kiwitea site, temperature was recorded at the trial site every 20 minutes at 0.5 m above ground level using HortPlus MicroLoggers (https://hortplus.com/microloggers). Meteorological data were compared with the long-term mean (LTM) (NIWA, 1980 – 2010) whenever data was available (Figure 4.1). In addition, solar radiation, evapotranspiration, and soil moisture data from NIWA are provided for the MU site (Figure 4.2) with the on-site measurement of volumetric soil moisture content (%) of each trial around maize silking time using Time Domain Reflectometer (TDR) Trase system, Model 6050X1 (Soil Moisture Equipment Corp., Santa Barbara, USA) at 15 cm depth (Table 4.4).

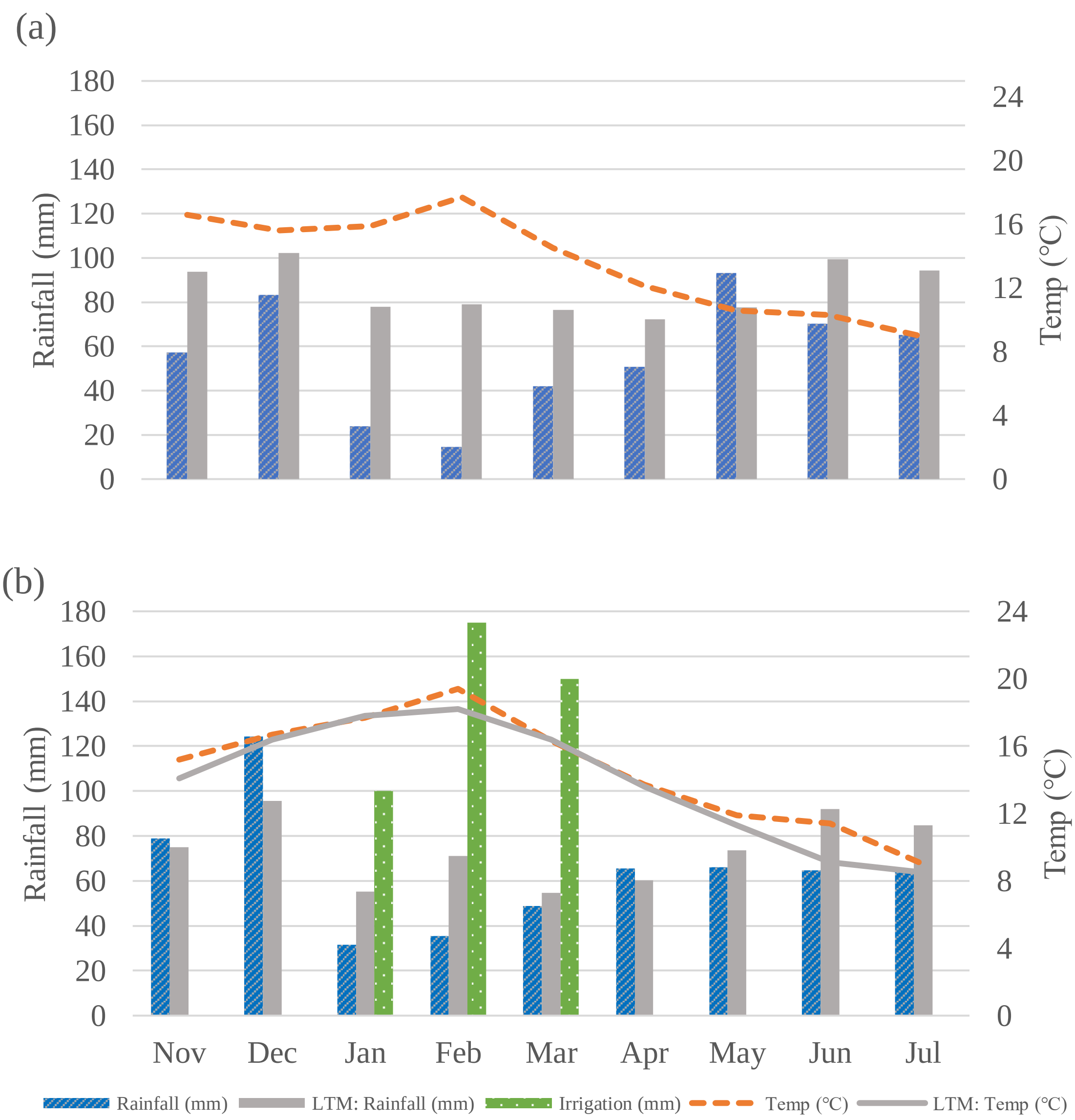


Figure 4.1. Mean monthly rainfall (mm) and temperature (°C) of (a) Kiwitea and (b) Massey University, Palmerston North, New Zealand compared with the NIWA long-term mean (LTM; 1980 – 2010) rainfall and temperature. Note: LTM temperature is not available at Kiwitea, and irrigation is only applied on the irrigated trial at the Massey University site.

4.3.6 Irrigation

Irrigation using a Zimmatic center pivot irrigation system was applied over the MU irrigated trial at a rate of 25 mm twice weekly between 10 January 2020 and 20 March 2020 (Table 4.3). This total irrigation (425 mm) was applied as the approximate replacement of the profile water lost by evapotranspiration (~400 mm water) during the summer (Figure 4.2) to prevent any limitation of moisture stress for the plant growth.

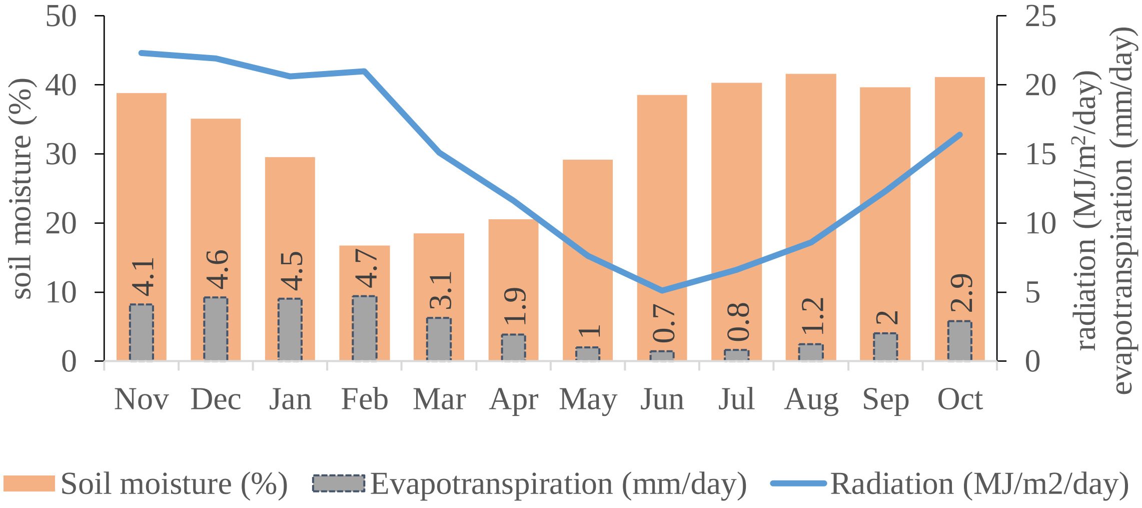


Figure 4.2. Mean monthly soil moisture (%) (20 cm depth), mean daily evapotranspiration (mm/day) and mean daily solar radiation (MJ/m^2/day) at Massey University site from November 2019 to October 2020 (NIWA).

Table 4.4. Soil moisture (%) of four experimental sites at 50% maize silking (average of five points measured using Time Domain Reflectometry (TDR) at 15 cm depth).

Sites	Soil moisture (%)						
	20 Jan	29 Jan	8 Feb	14 Feb	24 Feb	1 Mar	11 Mar
MU irrigated	22.5	33.2	34.3	30.0	33.0	30.4	35.3
MU non-irrigated	2.8	17.8	10.4	5.8	17.1	13.6	11.8
MU late	-	23.5	9.1	15.2	18.7	12.2	11.0
Kiwitea late	-	-	-	5.3	14.3	12.1	11.1

4.3.7 Number of leaves per plant

Numbers of fully expanded leaves were counted on five marked contiguous plants at 10-12 days interval approximately from 4 to 12 weeks after sowing (until tasselling of maize) in all trials. Leaves number six and 10 of maize plants were tagged when they appeared. Similarly, the tip of the last counted (youngest) leaf was marked with paints in WFC (see Plate 3.4, Chapter 3). All the tagged and painted leaves were used as reference points in counting the total number of leaves. Although some plants were lost at a later stage, substitution was not made due to very few lost plants in the trial, and we were able to maintain a minimum of 4 plants for average in the analysis. Along with leaf counts, the silking time, day to 50% silking and date were recorded in maize to estimate the harvest time. Leaf number per plant was plotted against the accumulated thermal time to compare the leaf appearance rate with the base temperature of 0℃ for fodder beet (Chakwizira et al., 2016b), 4℃ for kale and swede (Adams et al., 2005; Fletcher et al., 2012) and 8℃ for maize (Tsimba et al., 2013c). Thermal time was calculated as follows:

$$TT = \left[\frac{(Tmax+Tmin)}{2}\right] - Tb$$

where, T_{max} = daily maximum temperature

T_{min} = daily minimum temperature

T_b = base temperature

4.3.8 Leaf area measurement

Leaf area index (LAI) is defined as one half the total leaf surface per unit ground area (Jonckheere et al., 2004). It refers to the green leaves contributing to photosynthesis. Leaf area index in this study is also referred to as 'canopy or foliage area index' since it is measuring all light-blocking objects (LI-COR, 2019) or light fraction (Danner et al., 2015). Leaf area index was measured at 10 – 14 days intervals using an LAI-2200 C plant canopy analyser (Li-COR Ltd. Lincoln, NE, USA). At the time of measurement, individual plots were visually divided into three parts to represent the plant canopy variation in the whole plot. A total of fifteen readings, one above- and four below-canopy readings from each part, per plot were recorded at least 0.5 m distance from the edge of the plot and excluding border rows, following the guidelines for row crops with homogeneous canopy (Danner et al., 2015; LI-COR, 2019). The measurements were mostly taken between 11 am and 2 pm to ensure uniform solar radiation conditions. To avoid any influence from the operator and to limit the reading of objects over the small plot, a 45° view cap was used on both above- and below-canopy readings. All LAI measurements were processed with FV2200 software (v 2.1.1) as well as checked for scattering correction with a 4A sequence K record (Danner et al., 2015; Kobayashi et al., 2013; LI-COR, 2019; Pearse et al., 2016).

4.3.9 Harvest and measurements

4.3.9.1 Maize

Where possible, maize plots were harvested when the crop had reached approximately 34% of the whole crop DM (Thant et al., 2020; Tsimba et al., 2014; Williams, 2012). Harvesting was late a few days beyond the optimum silage maize harvest time at MU late and Kiwitea late trials due to COVID-19 travel restrictions in NZ from 25 March to 13 May 2020. The detailed harvest times of each experiment are given in Table 4.3. The middle two rows (4 m length in total) were cut at 10 cm above ground level. The fresh weights were weighed in the field and six representative sample plants from each plot were taken. Of six, three plants were used for DM assessment while the other three were used for plant component partitioning. The components were divided into leaf, stem, cob, and grain. The remaining three sample plants were mulched (AlKo dynamics 2200 S mulcher) to allow determination of silage DM and feed quality. The mulched samples were dried at 70℃ to a constant weight. After taking the silage DM sample, about 500 g of the mulch samples were kept in the freezer at -20°C before freeze-drying for feed quality analysis.

4.3.9.2 Winter forage crops

Winter forage crops were harvested between the 25 and 28 July 2020 across all four sites (Table 4.3). Four 1-m lengths were randomly chosen for DM yield analysis from each plot. Kale was cut from the ground level. Fodder beet and swede were pulled out from the ground and soil removed before weighing. After field weighing six representative sample plants were taken, three were oven dried as separate plant components (stem/bulb and leaf) at 70°C to constant weight for DM analysis and plant component ratio. From the remaining three plants, about 500 g of stem/bulb and leaf samples (slice and sealed in zipped bags) were kept in the freezer at -20°C before freeze-drying for feed quality analysis.

4.3.10 Maize yield loss estimation

At the MU late trial, maize grain may have been impacted by bird damage, and to account for this, a covariate analysis was conducted (Table S 4.4). A significant yield difference was observed between damaged and undamaged yields in both maize hybrids. To account for yield losses, plot yield was simply calculated with the average normal (undamaged) plant yield multiplied by the plant population per harvest area (4-m cut) as follows.

Yield (kg DM/plot) = normal plant yield (kg/plant) × plant population/plot × DM (%)

Then, plot yield was consequently adjusted to obtain the DM yield per hectare of maize in the MU late trial.

4.3.11 Feed quality analysis

Samples to be submitted for feed quality analysis were initially freeze-dried at the Nutrition Laboratory, School of Food and Advanced Technology, MU (Palmerston North, NZ). After freeze-drying, the dried samples were ground with a Cyclone Mill (1.0 mm screen), and then, approximately 40 g samples were sent to Hill Laboratories, Hamilton. Winter forage crops were analysed with the stem/bulb and leaf components separately, whereas maize was a mulched silage sample. Samples were analysed for metabolizable energy (ME), crude protein (CP), soluble sugars and starch (SSS), acid detergent fibre (ADF), and neutral detergent fibre (NDF) using near-infrared reflectance spectroscopy (NIRS). The % DM values are reported as a percentage (%) and ME value as MJ/kg DM.

4.3.12 Statistical analysis

Data analysis was performed using SAS software version 9.4 (SAS Institute Inc., Cary NC, 2016). For each experiment, data were analysed using the PROC ANOVA model and the means were separated with the Fisher's protected least significant difference (LSD) test when the ANOVA *F* value was significant ($P < 0.05$). The two-way ANOVA in PROC GLM was used to investigate the effect of irrigation and the site differences on yield and feed qualities of forage crops. To determine the interaction effect, the four experiments were analysed into two sets of comparisons: MU irrigated vs MU non-irrigated and MU late vs Kiwitea late experiments. The least square mean (LS means) was used to separate the treatments between managements (i.e. irrigation or site) using PDIFF mean separation test after the two-way ANOVA. Before undertaking data analyses, the homogeneity of variance (HOV) was tested using Bartlett's, Brown-Forsythe, and Levene's tests. The parameters which were assessed as not homogeneous were transformed using log transformation and checked whether inferences made had changed. When the inference had changed, it was reported accordingly (e.g. yields between MU late and Kiwitea late).

The Proc GLM procedure was used to analyse linear regression slopes for leaf appearance rate against the accumulated thermal time. Mean leaf appearance rates were separated with the LSD test. To characterise the relationship between yield and feed qualities, Pearson's correlation coefficient (r) was calculated and illustrated using the *corr_coef ( )* function of the *metan* package in R software (R v.4.0.3) (Olivoto & Lúcio, 2020). The R package *ggplot* and Microsoft Excel were used for the graphical presentation.

4.4 Results

4.4.1 Weather analysis

The total rainfall during the cropping season (November 2019 – July 2020) was 580 mm and 500 mm at the MU site and the Kiwitea site, respectively. These rainfall amounts were lower than the LTM rainfall: 82 mm less at the MU site and 273 mm less at the Kiwitea site. At both sites, the monthly rainfall was generally lower than the LTM rainfall, except for December at MU and May at Kiwitea. The minimum rainfall occurred between January and March (Figure 4.1), coinciding with the greatest evapotranspiration losses (Figure 4.2).

The average temperatures during the growing season (November – July) were 14.6℃ and 14.2℃ at the MU site and the Kiwitea site, respectively. This seasonal average temperature was about 0.7℃ higher than the LTM average at the MU site, but no LTM temperature data was available at the Kiwitea site. The maximum mean monthly temperature occurred in February at both sites: 19.4°C at MU and 17.7°C at Kiwitea.

At the MU site, solar radiation was greatest from November to mid-February (average 21.5 MJ/m^2) and least from May to July (average 6.4 MJ/m^2) (Figure 4.2). Radiation data was not available at Kiwitea but was assumed to follow a similar trend given its proximity to the MU site.

4.4.2 Plant population

The final plant population was recorded at the final harvest (Table 4.5). To compare the effect of irrigation and site on yield, the plant population was firstly assessed in each set of comparisons. There was no statistical difference for each treatment in each pair of experiments.

Table 4.5. Plant population (plants/ha) of forage crops across four experiments at Massey University and Kiwitea, New Zealand during the 2019 – 2020 season.

Treatment	Plant population (plant/ha)		
	MUI	**MUNI**	**Sig**[a]
P8805	116,210	127,029	NS
P9400	122,011	137,372	NS
Kale	266,667	316,667	NS
Swede	204,167	187,500	NS
Fodder beet	89,583	93,750	NS
	MUL	**KL**	**Sig**
P8000	144,670	132,827	NS
P8805	132,670	136,883	NS
Kale	287,500	354,167	NS
Swede	216,667	204,167	NS
Fodder beet	102,083	58,333	NS

MUI = Massey University irrigated; MUNI = Massey University Non-irrigated; MUL = Massey University late; KL = Kiwitea late trials

[a] Within a treatment, least square means are significantly different between managements (i.e. irrigation or site) using PDIFF mean separation test after the two-way ANOVA.

NS non-significant.

4.4.3 Maize silking time

The thermal time requirement ($SilkTT_8$) and days to 50% silking were different between the two hybrids at all locations (Table 4.6). However, the differences in 50% siking date was about 2 days on average, so the harvest time was adjusted to harvest the two hybrids at the same time. Maize hybrids required the longer days to 50% silking time at Kiwitea due to the cooler temperature with a higher altitude (380 m asl) compared with the MU late trial despite of the same sowing date.

Table 4.6. Maize silking thermal time requirements, days to and dates of 50% silking in 2019 – 2020.

Sites	Hybrid	$SilkTT_8$ (°Cd)	Days to 50% silking	50% silking date
MU irrigated	P8805	682.3±2.5**	82.8±0.3**	23-Jan-20
	P9400	716.4±8.2**	85.5±0.6**	26-Jan-20
MU non-irrigated	P8805	691.1±3.6***	83.5±0.3***	24-Jan-20
	P9400	739.1±3.3***	87.3±0.3***	27-Jan-20
MU late	P8000	704.7±3.4*	73.0±0.4*	10-Feb-20
	P8805	715.5±1.9*	74.3±0.3*	11-Feb-20
Kiwitea late	P8000	697.1±4.5*	82.0±0.4*	19-Feb-20
	P8805	717.8±5.6*	84.0±0.6*	21-Feb-20

maize hybrids were compared at each site and a t-test used to determine which means are statistically different at the probability *P<0.05, **P<0.01, ***P<0.001. Error values indicate a ± standard error of the means.

4.4.4 Leaf appearance rate

Leaf development was compared among the crops based on the accumulated thermal time. The number of leaves per plant was plotted against with the thermal time in Figure 4.3. In all trials, maize had the fastest leaf development (Figure 4.3) with the phyllochron of 48.4 – 54.6°Cd/leaf among the forage crops (Table 4.7). Generally, fodder beet leaves developed more slowly during the early stage but had a faster leaf development (69.0°Cd/leaf) at the MU late trial than in the other trials (92.8 – 144.7°Cd/leaf) (Figure 4.3 and Table 4.7). Kale and swede were slow in leaf development with the lower leaf number per plant for ~12 weeks measurement (Figure 4.3). The phyllochron of kale and swede were not significant with fodder beet except in the MU late trial (Table 4.7). Irrigation increased the leaf appearance of all crops compared with the non-irrigated treatments (Figure 4.3 and Table 4.7).

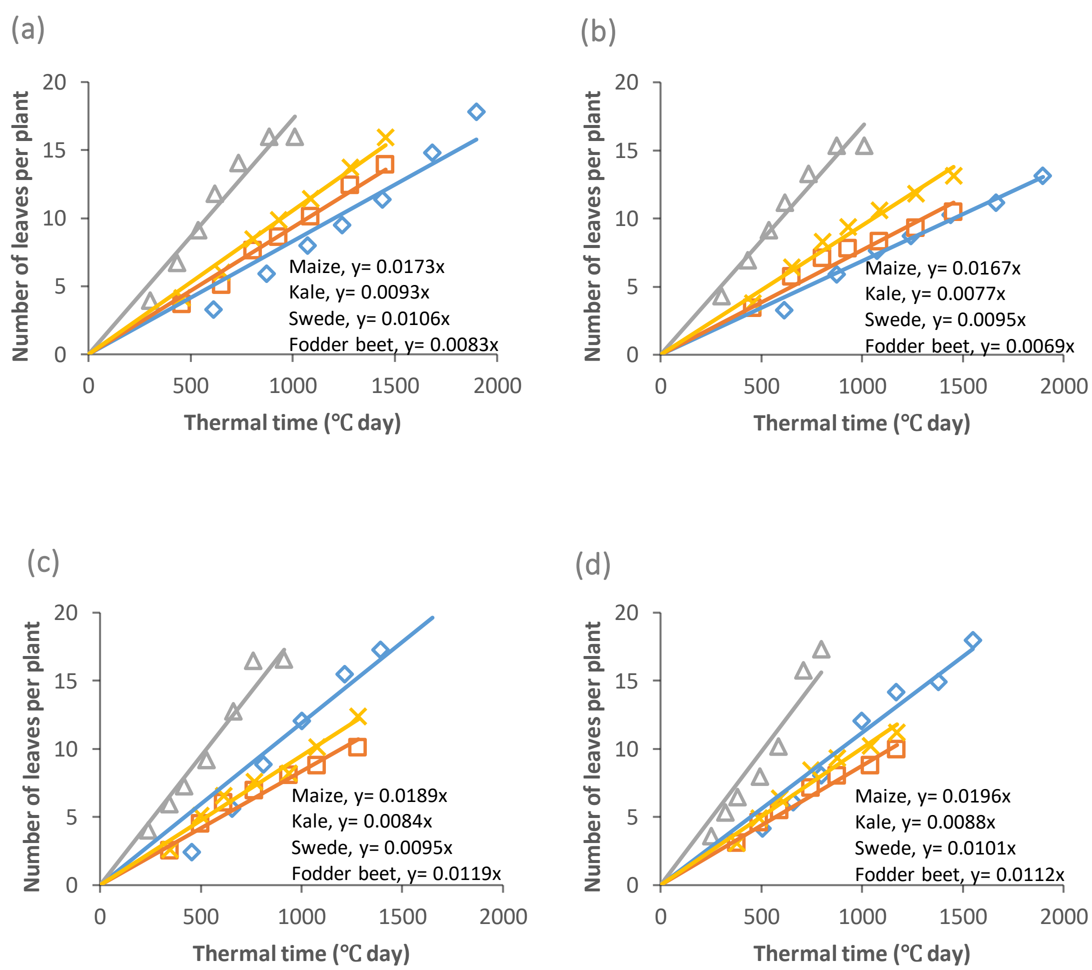


Figure 4.3. Leaf development of forage crops with accumulated thermal time in (a) MU irrigated, (b) MU non-irrigated, and (c) MU late trials at Massey University, and (d) Kiwitea late trial at Kiwitea, New Zealand during the 2019 – 2020 season (R^2 = 0.99). Base temperatures (T_b) are 8°C for maize (△), 0°C for fodder beet (◊), and 4°C for swede

(×) and kale (□). Note: P8805 maize hybrid was used for a comparison because it was common at all locations.

Table 4.7. Phyllochron of forage crops grown at Massey University and Kiwitea, New Zealand during the 2019 – 2020 season.

	MU irrigated	MU non-irrigated	MU late	Kiwitea late	
Crop			°Cd		Average
Maize[a]	52.1	54.6	51.4	48.4	51.6
Fodder beet	92.8	144.7	69.0	102.8	102.3
Kale	104.7	167.5	137.7	126.8	134.2
Swede	86.6	114.8	120.1	111.0	108.1
LSD $_{(0.05)}$	25.1	58.5	57.4	61.5	
			Significance		
Crop × TT	NS	NS	NS	NS	
TT	NS	NS	NS	0.0204	
Crop	0.0188	0.0147	0.0163	NS	

TT = Thermal time (°Cd), NS not significant.

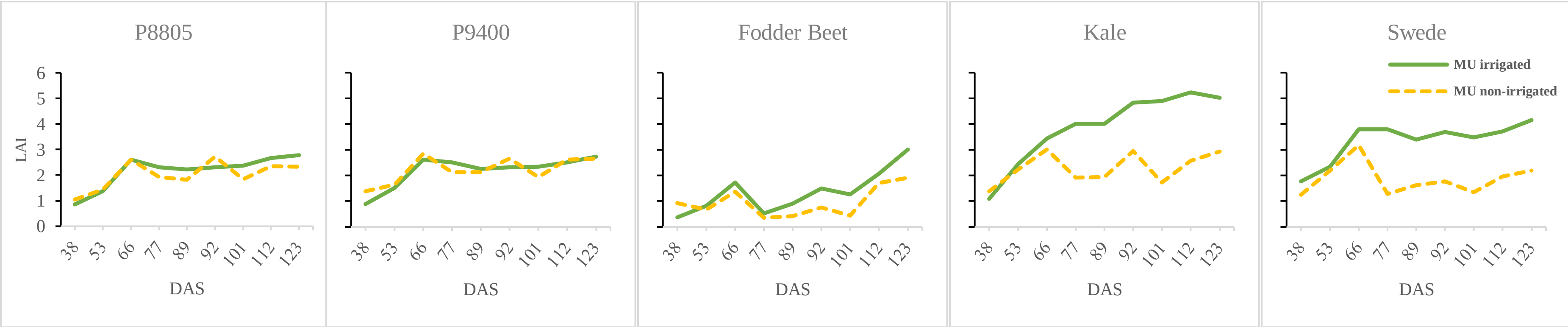
[a] P8805 maize was used since it was common for all trials

4.4.5 Leaf area index (LAI)

Irrigation generally increased the LAI of forage crops compared with the non-irrigated trial (Figure 4.4 [a]). The leaf area expanded rapidly in all forage crops between 38 and 66 DAS (days after sowing), but the rate and duration varied with the crop type; for example, there was a rise and fall in the leaf area of fodder beet and forage brassicas at the non-irrigated trial. The maximum LAI observed were 2.8 and 2.7 in P8805, 2.7 and 2.6 in P9400, 3.0 and 1.9 in fodder beet, 5.2 and 3.0 in kale, and 4.2 and 3.2 in swede, for the irrigated and non-irrigated trials, respectively.

Forage crops in the MU late trial achieved greater LAI than in the Kiwitea trial (Figure 4.4 [b]). In general, leaf area expanded rapidly in all crops between 39 and 99 DAS in the MU late trial while leaf area varied at Kiwitea. Maximum LAI's observed were 3.5 and 2.3 in P8805, 3.2 and 3.0 in P8000, 4.5 and 2.6 in fodder beet, 4.1 and 3.1 in kale, and 4.1 and 3.3 in swede, for the MU late and Kiwitea sites, respectively.

(a)



(b)

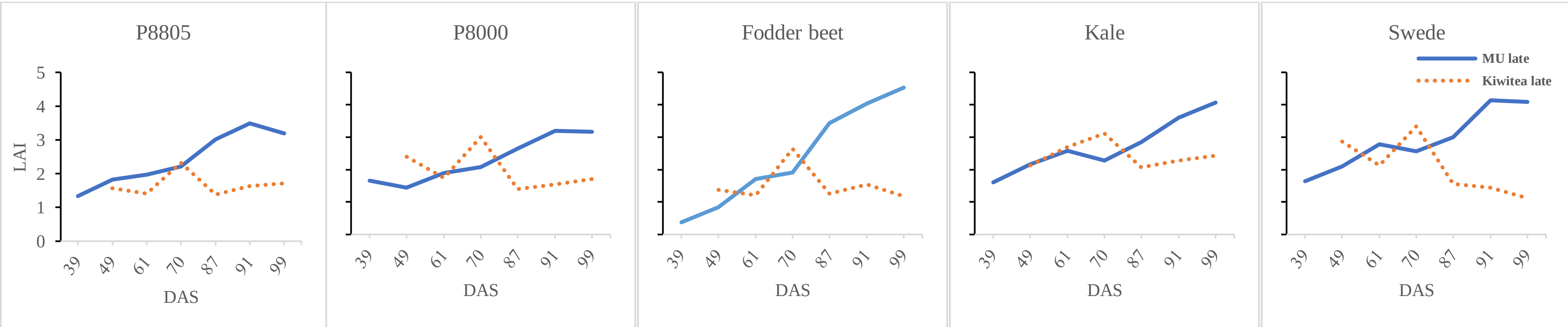


Figure 4.4. Leaf area index (LAI) of forage crops for (a) MU irrigated and MU non-irrigated trials (irrigation management), and (b) MU late and Kiwitea late trials (site differences). DAS – Days after sowing.

4.4.6 Maize yield components

Maize yield components consisted of leaf, stem, cob, and grain components (Figure 4.5). More than half of the total yield was grain in both P8000 and P8805 at the MU late and the Kiwitea late experiments. Thus, the harvest index (grain to grain + stover ratio) was generally above 0.5 in both hybrids. However, there was no difference in the proportion of each component between MU late and Kiwitea late trials apart from a higher % of leaves in both hybrids at Kiwitea.

4.4.7 Leaf and stem/bulb proportion of winter forage crops

Across all trials, 58 – 75% of the total yield was produced in the stem of kale plants. Similarly, 77 – 88% and 74 – 90% of total yield were found in the bulbs of fodder beet and swede, respectively (Figure 4.5). Plant components for WFC were influenced slightly by irrigation management. Irrigation significantly increased the proportion of fodder beet bulb and kale stem components compared with non-irrigated (Figure 4.5). Site influenced swede yield components; the leaf % at Kiwitea (26%) was much higher than other trials (Figure 4.5).

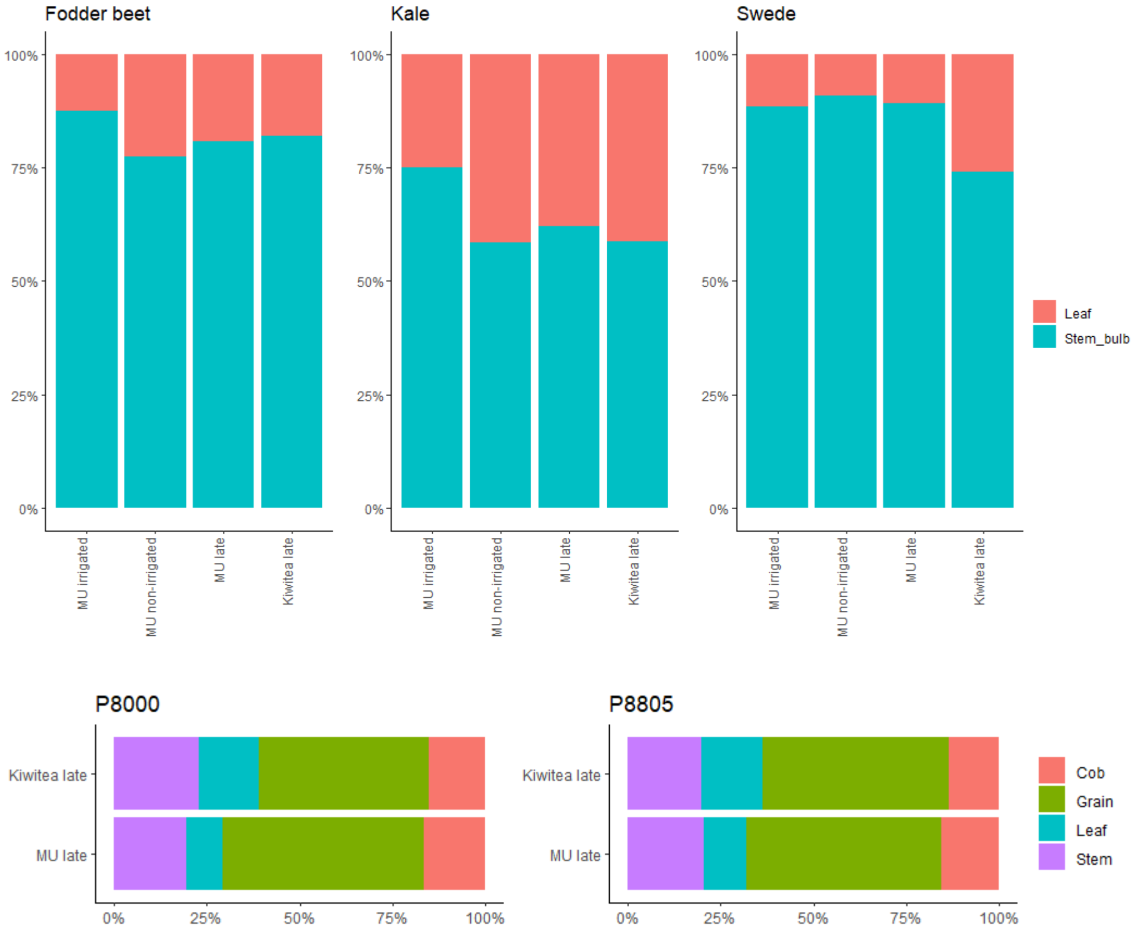


Figure 4.5. Crop yield components for maize and winter forage crops grown at Massey University and Kiwitea, New Zealand during the 2019 – 2020 season. LSD values of winter forage crops: fodder beet – 5.5; kale – 9.0; swede – 5.0 for each component. LSD values of maize: P8000 – 7.1, 3.6, 9.2, 5.0 and P8805 – 2.5, 2.5, 5.0, 5.2 for stem, leaf, grain, and cob, respectively.

4.4.8 Dry matter yield

Dry matter yields among forage crops were significantly different in each trial (Table 4.8). The two maize hybrids in each trial produced a higher DM yield than the WFC except at Kiwitea, where the maize yields were similar to kale and swede. No yield differences were observed between the two maize hybrids in any trial. Italian ryegrass planted after the maize harvest produced an additional yield of 1,209 – 2,761 kg DM/ha in the MU irrigated and MU non-irrigated trials. Kale and swede gave similar yields at all trials except a higher kale yield in the MU irrigated trial. Fodder beet yield was significantly lower than swede and kale at Kiwitea while the reverse trend was observed at the MU late trial.

Table 4.8. Dry matter yield of forage crops conducted at Massey University and Kiwitea sites in New Zealand during the 2019 – 2020 season.

Treatment	Yield (kg DM/ha)			
	MUI	**MUNI**	**Difference**	***Sig*** [a]
P8805	26220 a (1209) [b]	18061 a (2761)	8159 (31%)	***
P9400	26792 a (1237)	17864 a (2576)	8928 (33%)	***
Kale	19278 b	7210 b	12068 (63%)	***
Swede	12233 c	4579 b	7654 (63%)	***
Fodder beet	10186 c	7264 b	2922 (29%)	NS
Pr > F	***	***		
	MUL	**KL**	**Difference**	
P8000	19507 ab	12165 a	7342 (38%)	***
P8805	22662 a	10940 a	11722 (52%)	**
Kale	7016 c	11827 a	-4811 (-41%)	*
Swede	8286 c	11632 a	-3346 (-29%)	*
Fodder beet	13581 b	7020 b	6561 (48%)	***
Pr > F	***	*		

MUI = Massey University irrigated; MUNI = Massey University Non-irrigated; MUL = Massey University late; KL = Kiwitea late trials

Mean values of forage crops followed by the same letters in the same column of each trial site are not significantly different at LSD ($\alpha = 0.05$) after one-way ANOVA.

[a] Within a treatment, least square means are significantly different between management regimes (i.e. irrigation or site) using PDIFF mean separation test after the two-way ANOVA. Significant levels are denoted as * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$, NS non-significant.

[b] Values in brackets are the additional dry matter yield from Italian ryegrass but excluded from analysis

Agronomic management influenced forage yields since there was an interaction effect under irrigation and site comparisons (Figure 4.6). Yield of all crops were increased by irrigation. For example, maize yielded 31% and 33% more in the MU irrigated trial than unirrigated P8805 and P9400, respectively (Table 4.8 and Figure 4.6 [a]). Similarly, irrigation significantly increased the yield of kale and swede crops by about 63% each compared with the MU non-irrigated trial (Table 4.8 and Figure 4.6 [a]).

Location significantly influenced yields. For example, maize yields were 38% and 52% greater for P8000 and P8805 respectively at the MU late trial compared with the Kiwitea site (Table 4.8 and Figure 4.6 [b]). Similarly, fodder beet produced a higher yield in the MU late trial while kale and swede had a greater yield at the Kiwitea late trial (Table 4.8 and Figure 4.6 [b]).

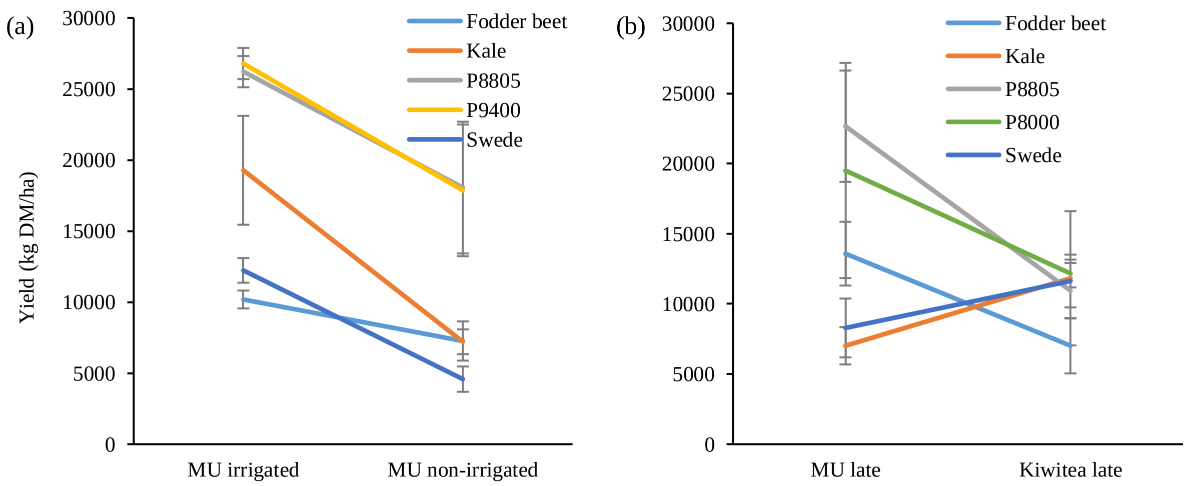


Figure 4.6. Effect of (a) irrigation (MU irrigated vs MU non-irrigated trials) and (b) site (MU late vs Kiwitea late trials) on dry matter yield (kg DM/ha) of different forage crops. Bars indicate the standard deviation. MU = Massey University.

Although irrigation and site differences were a focus of this study, the inclusion of planting date also provided useful insight, comparing the MU non irrigated late and early trials (one-month difference in planting date) (Table 4.8).

4.4.9 Feed quality

Forage crops differed significantly in all feed quality attributes in all trials (Table 4.9). Across all trials, ME content ranged from 9.9 MJ/kg DM (maize – P9400 in MU non-irrigated trial) to 14.9 MJ/kg DM (fodder beet in MU irrigated and Kiwitea late trials). In general, fodder beet and maize had, respectively, the highest and lowest ME values. On average, forage crop CP values were lowest in maize (7.4%) and highest in swede (14.8%). The soluble sugar and starch contents of forage crops ranged from 25.2 to 59.5% across all the trials. The SSS values differed among the forage crops with the highest value in fodder beet in all trials. Acid detergent fibre ranged from 6.1 to 23.6% across all trials. Fodder beet showed the lowest ADF content in all trials while kale was the greatest. Similarly, NDF ranged from 11.6 to 50.0% across all trials, with the lowest values in fodder beet (11.6 – 13.0%) while maize hybrid (P9400) was the highest (42.6 – 50.0%).

Table 4.9. Feed quality attributes of forage crops at Massey University and Kiwitea sites in New Zealand during the 2019 – 2020 season.

Treatment	**Feed quality attributes**														
	ME (MJ/kg DM)			**CP (%)**			**SSS (%)**			**ADF (%)**			**NDF (%)**		
	MUI	MUNI	*Sig*[a]	MUI	MUNI	*Sig*	MUI	MUNI	*Sig*	MUI	MUNI	*Sig*	MUI	MUNI	*Sig*
P8805	11.1 c	11.1 c	NS	7.9 b	7.3 c	NS	36.0 c	36.4 b	NS	17.8 b	18.2 b	NS	42.9 a	41.2 b	NS
P9400	10.9 c	9.9 d	***	8.2 b	6.5 c	NS	34.9 c	26.6 d	**	18.3 b	23.6 a	***	42.6 a	50.0 a	**
Kale	11.2 c	12.3 b	***	8.3 b	12.7 ab	***	32.8 c	31.4 c	NS	22.8 a	18.0 b	***	35.7 b	27.8 c	**
Swede	14.2 b	14.3 a	NS	11.4 a	14.3 a	*	42.1 b	37.8 b	NS	13.6 c	14.0 c	NS	17.7 c	19.2 d	NS
Fodder beet	14.9 a	14.7 a	NS	7.6 b	10.4 b	*	59.5 a	56.0 a	NS	6.1 d	6.8 d	NS	11.6 d	13.0 e	NS
Pr > F	***	***		**	***		***	***		***	***		***	***	
	MUL	KL	*Sig*	MUL	KL	*Sig*	MUL	KL	*Sig*	MUL	KL	*Sig*	MUL	KL	*Sig*
P8000	12.0 d	11.3 d	*	9.2 d	5.7 c	**	45.0 b	37.7 b	*	13.5 b	17.9 a	**	38.4 a	40.9 a	NS
P8805	12.2 d	11.9 c	NS	8.2 d	6.4 c	NS	46.4 b	42.5 b	NS	13.1 b	15.4 b	NS	34.7 a	36.1 b	NS
Kale	13.0 c	12.7 b	NS	16.1 b	16.6 a	NS	30.9 c	25.2 c	NS	16.6 a	17.9 a	NS	24.1 b	24.9 c	NS
Swede	14.1 b	14.5 a	NS	18.2 a	15.5 a	*	33.2 c	40.2 b	*	13.6 ab	10.5 c	*	19.1 c	14.4 d	**
Fodder beet	14.8 a	14.9 a	NS	11.2 c	9.6 b	NS	56.7 a	54.3 a	NS	6.4 c	6.7 d	NS	12.2 d	12.8 d	NS
Pr > F	***	***		***	***		***	***		***	***		***	***	
Optimum[b]	10 – 11			>12			36 – 44			>21			>33		

MUI = Massey University irrigated; MUNI = Massey University Non-irrigated; MUL = Massey University late; KL = Kiwitea late trials

ME = metabolisable energy (MJ/kg DM); CP = crude protein (%); SSS = soluble sugars and starch (%); ADF = acid detergent fibre (%); NDF = neutral detergent fibre (%)

Mean values followed by the same letters in the same column of each trial site are not significant at LSD ($\alpha = 0.05$) after one-way ANOVA.

[a] Within a treatment, least square means are significantly different between managements (i.e. irrigation or site) using PDIFF mean separation test after the two-way ANOVA. Significant levels are denoted as at * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$, NS non-significant.

[b] Optimum feed quality range for cow requirements (National Research Council, 2001; Nichol et al., 2003).

There was a significant interaction between irrigation and crop species for all feed quality attributes with the exception of SSS content (Table 4.9 and Figure 4.7 [a-e]). In general, P9400 maize had higher ME contents when irrigated but lower fibre content (ADF and NDF). However, this contrasted with the response in WFC, particularly kale.

Comparing the MU late and Kiwitea late sites, significant interactions were revealed between sites and forage crops for feed qualities except ME content (Table 4.9 and Figure 4.7 [f-j]). The CP contents in P8000 and swede crops were significantly higher at MU late compared with the Kiwitea late trial. At the Kiwitea site, swede had higher SSS while maize (P8000) showed a significant decrease. In contrast, the reverse was seen in ADF values in these crops. The NDF values were not affected by sites except for a significant decrease in swedes at Kiwitea.

Late planted forage crops produced greater values of ME, CP, and SSS compared with the early MU non-irrigated trial; they were also lower in fibre (ADF and NDF) (Table 4.9).

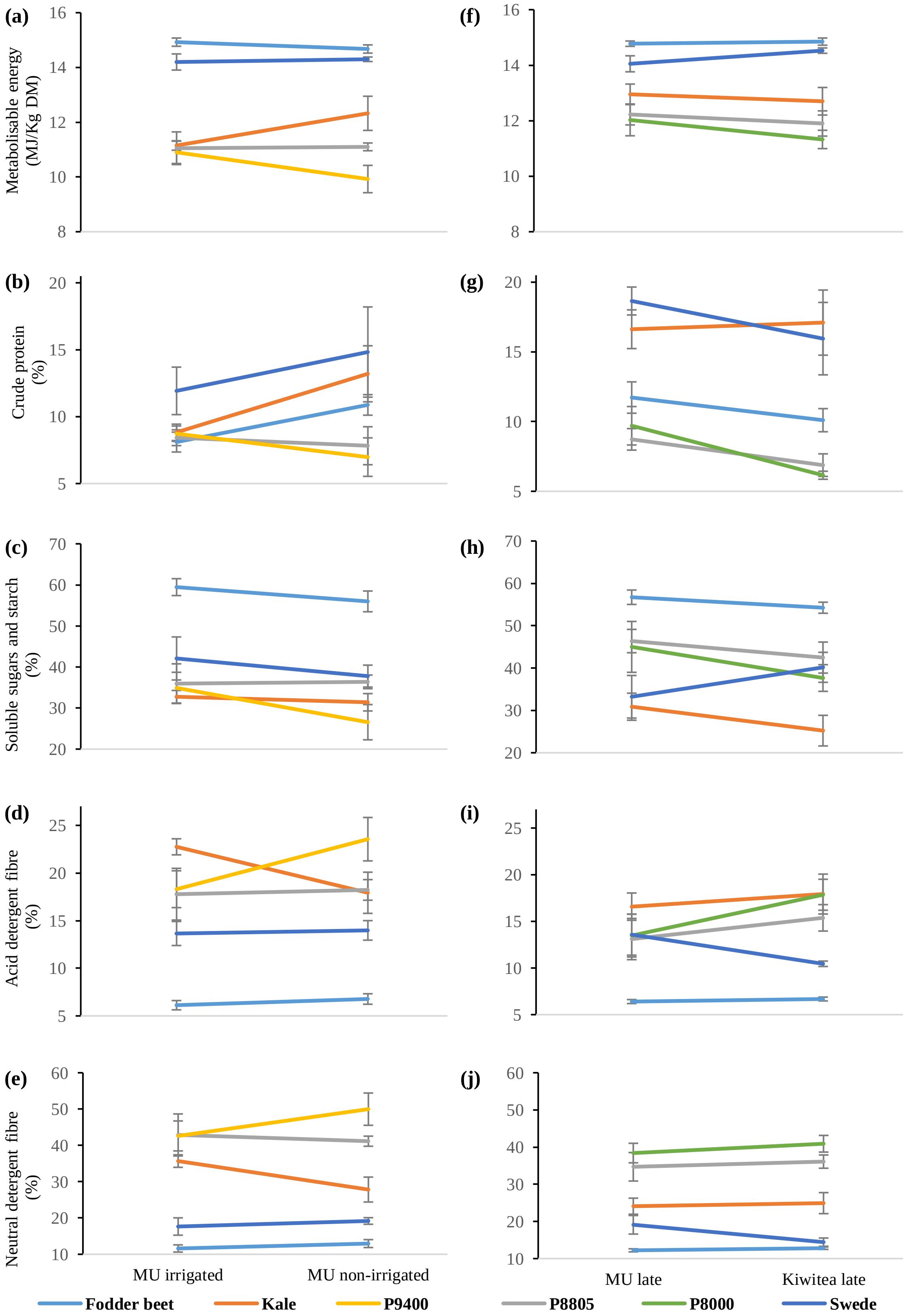


Figure 4.7. Effect of irrigation [a - e] (MU irrigated vs MU non-irrigated) and sites [f - j] (MU late vs Kiwitea late) on feed quality attributes - metabolisable energy (MJ/kg DM), crude protein (%), soluble sugars and starch (%), acid detergent fibre (%) and neutral detergent fibre (%) of forage crops in New Zealand. Bars indicate the standard deviation at P < 0.05. MU = Massey University.

4.4.10 Correlation analysis

Pearson correlation analysis was performed between DM yield and feed quality attributes (Figure 4.8). Dry matter yield was significantly and positively correlated with both fibre contents (ADF, r = 0.38 and NDF, r = 0.64) but a moderate negative correlation with ME (r = -0.61) and CP (r = -0.49). Similarly, ME had a highly significant positive correlation with CP (r = 0.48) and SSS (r = 0.64). In contrast to ME, CP was a weak negative relationship with SSS (r = -0.27). ADF and NDF were strongly and positively correlated (r = 0.82) but moderately to strongly negatively correlated with CP, ME, and SSS.

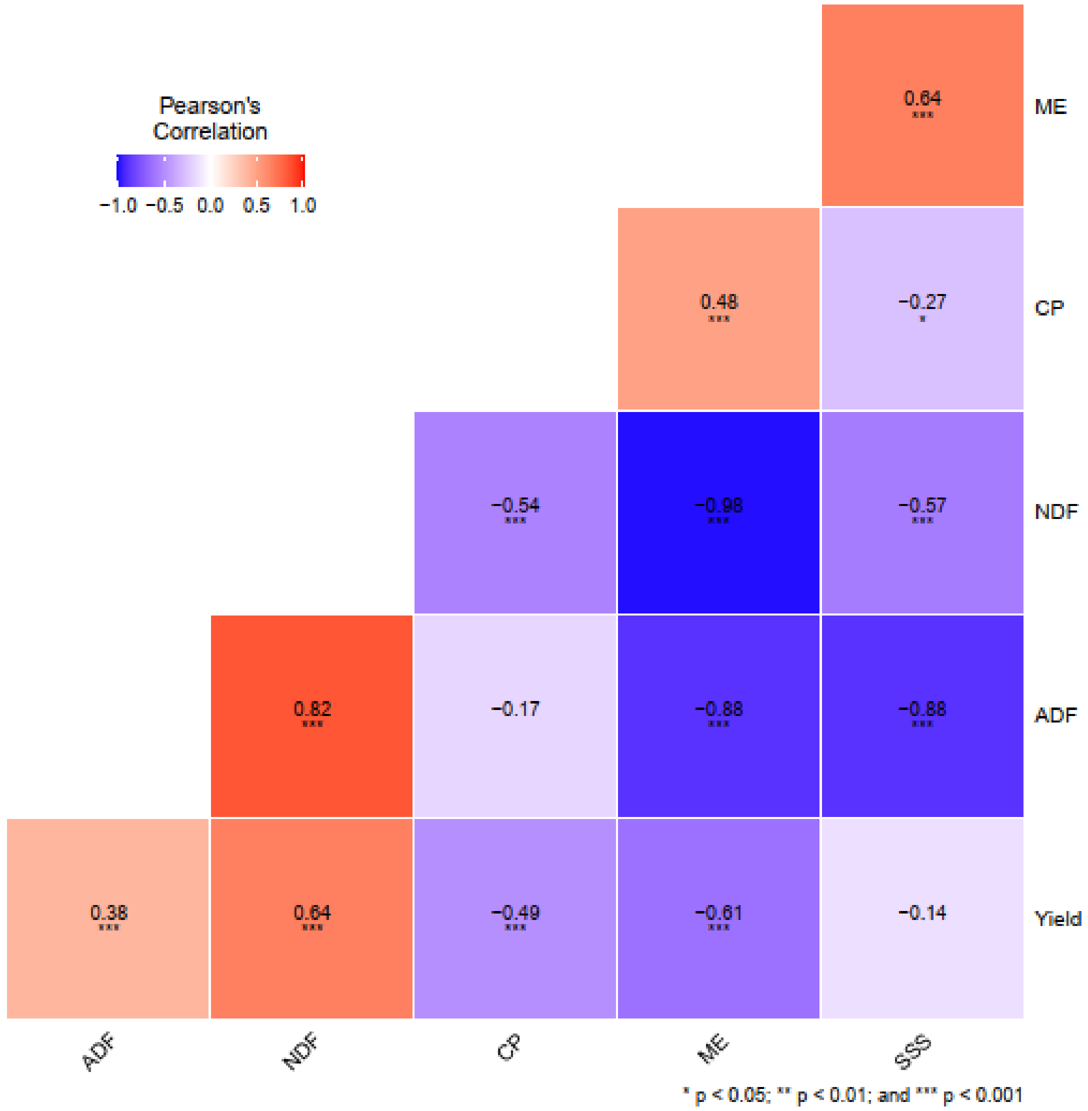


Figure 4.8. Pearson correlation coefficient matrix of yield and feed quality attributes measured combining across four experiments (n=80). Significance correlations are denoted by * P < 0.05; ** P < 0.01; *** P < 0.001. Yield = dry matter yield (kg DM/ha); ME = metabolisable energy (MJ/kg DM); CP = crude protein (%); SSS = soluble sugars and starch (%); ADF = acid detergent fibre (%); NDF = neutral detergent fibre (%).

4.5 Discussion

This discussion section consists of three main parts: crop development, dry matter yield, and feed quality. Crop development comprises plant population of crops, leaf development characteristics, leaf area index, and crop yield components. The relationship of crop development to yields is discussed in the context of the research findings. Similarly, dry matter yield and feed quality of forage crops are firstly outlined and compared with the existing literature, then discussed the effect of irrigation and site differences on yield and quality of forage crops.

4.5.1 Crop development

4.5.1.1 Plant population

In all trials, forage crops attained the expected plant population (Table 4.5). For example, maize reached the maximum yield range plant population recommended for the lower North Island region of NZ (Genetic Technologies, 2018). Both kale and swede also attained the optimum plant population, 25 and 20 plants/m^2 respectively (de Ruiter et al., 2009b; Zyskowski et al., 2004) although the population decreased periodically due to the natural self-thinning behaviour (de Ruiter & Edwards, 2011; Zyskowski et al., 2004). Fodder beet was also in the optimum plant population range (7-10 plants/m^2) (Khaembah et al., 2017; Khaembah et al., 2019) except the Kiwitea site.

4.5.1.2 Leaf development

The rapid leaf appearance rate of maize has the advantage of faster canopy closure although it has a wider spacing (70 cm) compared with other crops in the trial. Maize leaves emerged at an average of 0.02 leaf per °Cd (i.e. phyllochron about 51.6°Cd/leaf) while WFC produced leaves 0.008 to 0.01 leaf per °Cd (i.e. phyllochron about 102.3 – 134.2°Cd/leaf) across all the trials (Table 4.7). With the early canopy closure, maize can suppress weeds at the early stage, allowing more efficient utilisation of nutrient and water among the forage crops. The rapid canopy closure also enables higher interception of radiation when it is plentiful in summer compared with other crops.

The phyllochron length was smaller under irrigation compared with the non-irrigated, which is warm and dry condition during the growing season. This is consistent with the previous findings (Tsimba et al., 2013c).

4.5.1.3 Leaf area index (LAI)

The critical LAI (90 – 95% of radiation interception (Moot et al., 2017)) and its duration on the plant are crucial to produce higher biomass yield. The critical LAI are described as 2 – 2.7 in maize (Baron et al., 2006), 3 – 4 in fodder beet (Chakwizira et al., 2016b), 3.4 or 3 – 5 in kale (Chakwizira et al., 2011b) and approximately 3.6 in swede (a value described in a similar crop, turnip) (Chakwizira & Fletcher, 2012). In this study, crops generally achieved the critical LAI at 66 and 90 DAS at the MU irrigated and the MU late trial, respectively while not or only for a short duration of achievement at MU non-irrigated and Kiwitea late trials (Figure 4.4). Fodder beet in the MU irrigated trial just achieved the critical LAI after four months of sowing (123 DAS), indicating slow crop development. Irrigation dramatically increased leaf expansion, particularly in kale and swede (Figure 4.4 [a]) but was inconsistent for other crops. The response of LAI to irrigation is consistent with other research in New Zealand (Chakwizira et al., 2016b). Differences in LAI of forage crops were more evident between the MU late and Kiwitea late trials (Figure 4.4 [b]), the latter receiving very low rainfall between January and February (Figure 4.1). Drought conditions would have reduced LAI at Kiwitea in all crops but LAI in the WFC recovered after the rain in late April (Figure 4.1 and Figure 4.4). On the other hand, large differences in LAI may also be due to the variations in temperature between the two sites; for example, 0.4℃ on average higher temperature at MU site compared with the cooler Kiwitea site during the crop season. Relatively small differences in temperature can affect the development of leaf area in maize (Tsimba et al., 2014).

4.5.1.4 Yield components

The contribution of different maize plant components to yield in this study is consistent with the previous research conducted in Palmerston North (Millner et al., 2005). Other studies have reported a wide range of grain contribution (35 – 57%) (Havilah, 2011; Tsimba, 2011). Similarly, the component ratio of WFC was consistent with previous reports. For example, the contribution of the stem in kale (58 – 75%) and bulb in fodder beet (77-88%) in this study were similar to several studies in NZ (Chakwizira et al., 2014a; de Ruiter et al., 2009b; Matthew et al., 2011; Milne et al., 2014; Wilson et al., 2004). However, the proportion of bulb in swedes in this study (except 74% at Kiwitea) was generally high compared with previous research (Chakwizira et al., 2011a; Gowers et al., 2006). Along with the cultivar difference, this could be mainly due to about 2 – 2.5 months longer crop duration (November – July) in this study compared to those previous research (December – May).

4.5.2 Dry matter yield

Maize yields were generally higher than the WFC in this study. This is, despite the shorter crop growth duration in maize. Rapid leaf area expansion of maize (Table 4.7) would have the advantage of enabling interception of more solar radiation than other crops when radiation levels are high, e.g. November to February (Figure 4.2). Sowing a permanent or short-term pasture after maize is harvested further increases the potential yield from this system (Table 4.8). It will also result in greater uptake of residual soil nitrogen (Teixeira et al., 2016; Zyskowski et al., 2016), reducing nitrogen leaching risks. The maize yields of 17,864 to 26,792 kg DM/ha at the MU located trials and 10,940 to 12,165 kg DM/ha at Kiwitea trial are consistent with previous reports (Chakwizira et al., 2017b; de Ruiter et al., 2009a; Densley et al., 2006; Densley et al., 2003; Densley et al., 2005; Foundation for Arable Research, 2020; Minnée et al., 2009; Thant et al., 2020; Tsimba et al., 2020). The higher maize yield at the MU site also reflects the early achievement of critical LAI compared with the Kiwitea site (Figure 4.4).

The yields of the WFC were generally similar to previous reports in NZ. For example, kale (7,016 – 19,278 kg DM/ha) (Chakwizira et al., 2015a; Chakwizira et al., 2015b, 2015c, 2017a; Chakwizira et al., 2013a; Westwood et al., 2014) and swede (4,579 – 12,233 kg DM/ha) (Chakwizira et al., 2011a; Chakwizira et al., 2012; Gowers et al., 2006; Thompson et al., 2012) were similar to reported yield ranges. However, fodder beet yields (7,020 – 13,581 kg DM/ha) in this study were lower than previous research (Chakwizira et al., 2016a; Chakwizira et al., 2014b; Chakwizira et al., 2018; Khaembah et al., 2021a; Matthew et al., 2011; Milne et al., 2014). This may be associated with the LAI achieved being lower than the critical LAI reported for fodder beet (3 – 4) (Chakwizira et al., 2016b) in all trials except MU late (Figure 4.4). Slow early establishment in fodder beet means it is not able to compete with weeds especially under dry conditions. Fodder beet is susceptible to limiting factors during the establishment period resulting in a wide range of yields (8 – 34 t DM/ha) (Judson et al., 2016).

4.5.2.1 Irrigation increases yield

Irrigation increased yields of all forage crops. Maize yields ranged from 17,864 kg DM/ha in the non-irrigated trial to 26,792 kg DM/ha in the irrigated trial, a 31 – 33% increase (Table 4.8). With its extensive rooting system, maize can capture more water from the depth (0 – 1.8 m) and produced 62 kg DM per mm of water used (26220 kg DM/ha vs 18061 kg DM/ha with 425 mm and no irrigation). A similar yield increment in maize by irrigation with similar N fertilisation (250 kg N/ha) was also observed by

Teixeira et al. (2014). Likewise, other research reported an increase in maize yield with a response of 50 kg DM/mm of water in a similar climate in Australia (Islam et al., 2012).

Fodder beet yields were not affected by irrigation (Table 4.8) which contradicts previous research in NZ (Chakwizira et al., 2014b; Chakwizira et al., 2018; Khaembah et al., 2021b). This is probably due to the similar rate of leaf area expansion and duration of critical LAI (≥3) between irrigated and non-irrigated fodder beet (Figure 4.4). In addition, fodder beet is less competitive with weeds during the early growth due to a slow development, reducing its water use efficiency. Kale and swede yields significantly increased with irrigation, consistent with previous reports (Chakwizira et al., 2013a; Fletcher et al., 2010a). This is possibly due to the total water use in irrigated trials (rainfall + irrigation) since forage brassicas respond to total water use (WU) than its water use efficiency (WUE), regarding an equation of yield = WU × WUE (Fletcher et al., 2010a). Another reason is probably the higher radiation interception under irrigation (Chakwizira et al., 2013a) through the early achievement of critical LAI (3 – 5 in kale (Chakwizira et al., 2011b)) and the maintenance of this leaf area throughout the growing season (Figure 4.4 [a]).

4.5.2.2 Site effect on yield

Overall, maize yields were greater than WFC yields in the MU late trial whereas maize yields were similar to kale and swede crops at Kiwitea. Kiwitea is a higher altitude site and therefore cooler than the MU site (Figure 4.1). Conversely, the greater yield of maize at the MU late trial can be attributed to the ample radiation and higher monthly temperature (~1.1℃ higher at MU site from November to April) (Figure 4.1) as well as slightly higher soil moisture content at silking (February) (Table 4.4).

In contrast to maize, forage brassicas (kale and swede) performed well at Kiwitea compared with MU. This was primarily due to both crops recovering from severe wilting (Plate 4.1) after rainfall in late April at Kiwitea (Figure 4.1). Fodder beet produced 13581 kg DM/ha at the MU late trial, about double the yield at Kiwitea (7020 kg DM/ha). A possible explanation could be the lower plant populations achieved at Kiwitea, although there was no statistical difference in plant population. However relatively small differences in plant population can result in significant yield differences (Chakwizira et al., 2013b). Another possible reason is susceptibility of fodder beet to drought at the early stages, e.g. daytime wilting (Ministry for Primary Industries, 2020a), with less ability to regrow after rain compared to swede. Cultivation immediately prior to planting at the MU late site, appeared to improve seedbed conditions greatly (de Ruiter & Edwards, 2011) and helped suppress weed establishment (Table 4.3); no supplementary weeding was required for the MU late trial.

Plate 4.1. Swede and kale plots at Kiwitea, New Zealand. Photos were taken on 15 March 2020 (left) and 28 May 2020 (right) following April rain.

4.5.2.3 Sowing date effect on yield

The sowing date effect is not directly compared between forage crops in this research since fertiliser splits and maize hybrids were not the same in the early sowing MU non-irrigated and MU late trials. However, the increased yield trend of all forage crops in MU late sowing trial is consistent with the leaf area development (Figure 4.4). Prior cultivation immediately before planting contributed to improved weed control for later planted crops (Table 4.3).

4.5.3 Feed quality

The quality profiles of forage crops are generally consistent with previous reports in NZ: for example, maize (Millner et al., 2005), kale (Chakwizira et al., 2015b; Westwood et al., 2014; Westwood & Mulcock, 2012), swede (Westwood & Mulcock, 2012), and fodder beet (Chakwizira et al., 2014a; Dalley et al., 2020b; Matthew et al., 2011). Metabolisable energy (ME) values (Table 4.9) in this study suggests that all crops can be considered as good to excellent quality using the criteria published by de Ruiter et al. (2007): excellent (>11.0 MJ ME/kg DM), acceptable (>9 MJ ME/kg DM), and poor quality (<9 MJ ME/kg DM). Metabolisable energy values also fall in the optimum range described in previous reports (Chakwizira et al., 2014a, 2015b; National Research Council, 2001; Nichol et al., 2003). Compared with results generated in the 2018/19 season (Thant et al., 2020), the ME values achieved in the 2019/20 season were considerably higher, possibly due to the samples from the later season being freeze-dried rather than oven dried. This is because freeze-drying had little effect on chemical composition of the samples compared with oven drying, especially under prolonged drying periods (Deinum & Maassen, 1994).

Crude protein content of 16 – 22%, 10 – 16%, and 5 – 12% are described as the optimum feed quality for lactating, non-lactating dairy cows and the best environmental outcomes (Dalley et al., 2017). The lower CP contents of maize and fodder beet coupled with higher SSS values can be considered as having good potential to reduce the urinary N excretion because forage with CP (<12%) and SSS (>25%) reduces the urea content of urine in cattle (Dalley et al., 2017; de Ruiter et al., 2019). In contrast, forage brassicas had a high CP content (>12%) with marginal SSS values (Table 4.9). However, both maize and fodder beet may probably need to be supplemented with a high protein feed (Dalley et al., 2017; de Ruiter et al., 2019; Kolver et al., 2001) to meet the recommended 12 – 18% protein requirements of cows (National Research Council, 2001; Nichol et al., 2003) or the proportion of feed on offer adjusted to increase the total protein intake (Nichol et al., 2003).

Both ADF and NDF are important for rumen function and animal health, particularly when high SSS feeds are included in the diet. Acid detergent fibre contents of all forage crops (Table 4.9) were lower than the minimum cow requirement (21% ADF) (National Research Council, 2001). Maize NDF values meet the recommended cow requirements while other crops are considerably low compared with recommended NDF content (33%) (National Research Council, 2001; Nichol et al., 2003). This low NDF could increase susceptibility to rumen acidosis through less chewing during grazing as well as reduced cud chewing. Less chewing means less saliva, which contains acidity buffers, which helps maintain a normal rumen pH (6.2 – 6.5) (Nichol et al., 2003). In addition to low NDF, the high non-structural carbohydrate (NSC) in forage brassicas or high sugar content (40 – 60%) in fodder beet can cause rumen pH to decrease because rumen microbes break down the NSC quickly to make volatile fatty acids (VFA) (Gibbs, 2014; Matthew et al., 2011; Nichol et al., 2003).

4.5.3.1 Irrigation effect on feed quality

Irrigation did not have a consistent effect on feed quality, particularly maize (P9400) and kale (Table 4.9 and Figure 4.7). The lower ME in maize (P9400) under non-irrigated conditions associated with lower SSS values in this study (Figure 4.8). Drought can reduce ME in maize because of lower starch contents in the grain, the major yield component (Gallo et al., 2014; Islam et al., 2012). Greater fibre content (ADF and NDF) in maize (P9400) in the unirrigated trial (Table 4.9 and Figure 4.7) is consistent with previous research (Gallo et al., 2014; Nematpour et al., 2021). This may be explained by the fact that cellulose, hemicellulose and lignin are affected by the water stress (Nematpour et al., 2021). On the other hand, the increase in kale's ME values under non-irrigated conditions is partly explained by its inverse relationship with both ADF and NDF fibre content (Figure 4.8). The decrease in CP measured in WFC under irrigation has been reported previously (de Ruiter et al., 2019). This could be the result of a negative association of CP with SSS ($r = -0.27$) and yield ($r = -0.49$) (Figure 4.8), supporting the general dilution effect (de Ruiter et al., 2019). Crude protein content can be influenced by the contribution to final yield of different components; leaves are higher in protein than the stems for example (Pelletier et al. 1976 cited in Chakwizira et al., 2015b). The high CP content in the MU unirrigated trial is associated with significantly greater leaf proportion than the MU irrigated trial, particularly in kale and fodder beet (Figure 4.5) (Chakwizira et al., 2015b).

4.5.3.2 Site effect on feed quality

Significant site × crop interactions were observed for CP, SSS, ADF, and NDF. The largest interactions were observed in P8000 maize and swede (Table 4.9 and Figure 4.7). Higher CP and SSS in maize (P8000) from the MU late trial may be due to higher grain to stover proportion (>50%) (Figure 4.5), probably due to the higher soil moisture at the time of silking at the MU site (Figure 4.2). In contrast, maize at Kiwitea had a greater fibre content (ADF and NDF), partly explained by a lower rainfall (91.5 mm less from November to April compared to MU late) and less soil moisture (water stress) that affected the cellulose, hemicellulose and lignin contents of ADF and NDF fibre (Gallo et al., 2014; Nematpour et al., 2021).

Kale had higher fibre contents compared to swede due to its longer and fibrous stems (Jung et al., 1986; Kunelius et al., 1989) but site differences did not affect its fibre contents. However, swede had a significant lower fibre at Kiwitea with a greater content of SSS, which is possibly due to a negative correlation between them (Figure 4.8).

4.5.3.3 Sowing date effect on feed quality

Sowing date may affect forage qualities because the increase in ME, CP, and SSS were generally observed in MU late trial compared to the early MU non-irrigated trial (Table 4.9). However, the maturity of crops at harvest should be considered in forage quality changes. The harvest of the WFC in the MU late trial was about one-month earlier than the MU non-irrigated trail (Table 4.3). Younger plants may have greater nutritive value (Albayrak & Yuksel, 2010). On the other hand, maize quality was good irrespective of planting date although harvest was delayed for 10 days at the MU late trial (Table 4.4) compared to that of early MU non-irrigated trial at the time of harvest.

4.6 Conclusion

Maize (10,940 – 26,792 kg DM/ha) overall produced greater yields than winter forage crops (4,579 – 19,278 kg DM/ha) but at the higher altitude Kiwitea site maize yields were similar to the WFC. The opportunity to resow pasture after maize silage harvest increases yield from the cropped area, increasing the competitiveness of maize. All crops produced forage with good ME contents however, crude protein content of maize and fodder beet (<12%) were low but this is potentially an advantage for reducing urinary N excretion. Fibre content was comparatively low in the swede and fodder beet crops. This is potentially a risk for animal health in ruminants. Irrigation increased the yield of all forage species from 29% to 63%. The effect of irrigation on feed quality was inconsistent. Kale had lower ME and CP but higher fibre (ADF and NDF) under irrigation, in contrast to maize. Overall, maize demonstrated an ability to produce high yields of adequate ME forage across a wide range of environments albeit with low protein content, a potentially useful trait for reducing N leaching.

4.7 Acknowledgement

The authors would like to thank Mark Osborne and Brian Smith for planting the trials and irrigation operations at the Massey University site. Our sincere thanks go to Karen Millner and Dr. Kyaw Min Tun, Dr. Allan Siano, Gautam Shrestha, Romana Mbinya, and Ling Hu for help with crop harvesting. We would like to also express our thanks to Genetic Technologies Limited and Agricom for supplying seeds. Finally, we would like to thank Damien Ross Humphrey (Director), Rowenda Farms Ltd. for providing the trial site at Kiwitea.

4.8 Supplementary materials

Table S 4.1. Summary of two-factor analysis of variance (ANOVA) for dry matter yield and feed quality attributes of forage crops in New Zealand in 2020 (n= 40 for each set of comparison).

	DM Yield	ME	CP	SSS	ADF	NDF
			MU irrigated vs non-irrigated trials			
Irrigation	***	NS	**	**	NS	NS
Crop	***	***	***	***	***	***
Irrigation × Crop	**	***	**	NS	***	***
			MU late vs Kiwitea late trials			
Site	**	NS	***	NS	NS	NS
Crop	***	***	***	***	***	***
Site × Crop	***	NS	**	*	**	*

Significance levels are denoted by * P < 0.05; ** P < 0.01; *** P < 0.001; NS non-significant. DM Yield = dry matter yield (kg DM/ha); ME = metabolisable energy (MJ/kg DM); CP = crude protein (% DM); SSS = soluble sugars and starch (% DM); ADF = acid detergent fibre (% DM); NDF = neutral detergent fibre (% DM)

Table S 4.2. Management/Locational effects on plant components of maize at Massey University and Kiwitea in 2020 season.

Site	Grain (%)	Cob (%)	Leaf (%)	Stem (%)	Silage DM (%)
			Maize P8000		
MU late	54.2	16.7	9.7	19.4	56.1
Kiwitea late	46.0	15.1	16.2	22.7	44.2
LSD (*P* = 0.05)	NS	NS	3.6	NS	6.8
P > F	0.0653	0.3761	0.0103	0.2260	0.0113
			Maize P8805		
MU late	52.6	15.4	11.5	20.5	54.1
Kiwitea late	50.3	13.4	16.6	19.7	44.0
LSD (*P* = 0.05)	NS	NS	2.5	NS	8.2
P > F	0.2319	0.3265	0.0074	0.3769	0.0294

NS, not significant. Note: data was not collected from MU irrigated and non-irrigated trials due to the COVID-19 lockdown on 25 March 2020.

Table S 4.3. Management/Locational effects on plant components of kale, swede, and fodder beet at Massey University and Kiwitea in 2020 season.

Site	Kale		Swede		Fodder beet	
	Leaf (%)	Stem (%)	Leaf (%)	Bulb (%)	Leaf (%)	Bulb (%)
MU irrigated	24.8	75.2	11.6	88.4	12.5	87.5
MU non-irrigated	42.2	57.8	9.4	90.6	22.6	77.4
MU late	37.8	62.2	10.9	89.1	19.3	80.7
Kiwitea late	40.4	59.6	26.2	73.8	18.5	81.5
LSD (P = 0.05)	9.0	9.0	5.0	5.0	5.5	5.5
P > F	0.0072	0.0072	0.0001	0.0001	0.0165	0.0165

NS, not significant.

Table S 4.4. Co-variate analysis of normal and damaged plants of maize hybrids (P8000 and P8805) impacted by birds at MU late trial.

Hybrid	Bird damage	Single plant yield (kg/plant)	Plot yield (kg/4 m cutting)
P8000	Normal	0.24	9.93
	Damaged	0.11	4.68
	P > |t|	0.0267	0.0240
P8805	Normal	0.30	11.13
	Damaged	0.18	6.53
	P > |t|	0.0011	0.0164

Chapter 5 Nitrate leaching modelling using APSIM

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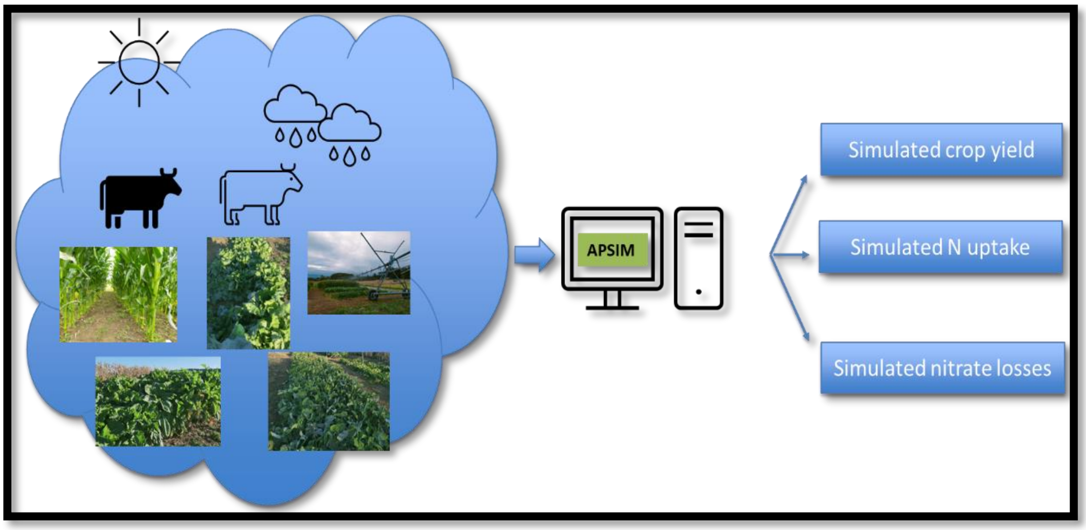

Chapter 5 is intended to publish in peer review journals.

5.1 Abstract

Excreted urine nitrogen (N) contributes significantly to N leaching losses in winter grazed paddocks in New Zealand (NZ). The crop yields and N content from the field study were used to estimate potential urine N excretion (per cow) and N loads (per ha) using a urinary-N excretion equation. The excreted N loads were analysed in **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM) to assess the potential influence of low N loads on nitrate leaching losses. Nitrate losses from maize silage, hereafter referred to as 'maize', cropping system (maize monocrop or maize-ryegrass) were compared with winter forage crops systems (kale, swede, and fodder beet). Management practices are processed in APSIM as irrigation regimes (0, 425 mm; based on field trials) and urine N deposition rates (N loads/ha) at the end of the cropping season. Urine N deposition rates are assumed as Control N loads (when crops are harvested = 0 N loads), Low N loads (when low crop yields and low forage N) and High N loads (when high crop yields and high forage N). Forages with low N content resulted in lower urine N excretion both on per cow and per hectare basis but the differences between forages were smaller on an area basis due to the greater influence of yield in the calculation. For example, maize produced the lowest urine N output per cow (30.9 – 64.3 g N/cow/day) while swede produced the highest (88.3 – 178.0 g N/cow/day). However, urine N loads over the two seasons ranged from 59.9 – 124.5 kg N/ha in maize and 47.1 – 201.4 kg N/ha in swede. Predicted nitrate leaching losses from maize (21 – 120 kg N/ha) were significantly less than the losses from brassica forage crops (69 – 201 kg N/ha in kale and 20 – 199 kg N/ha in swede) but similar to fodder beet's nitrate losses (18 – 126 kg N/ha). Ryegrass planted immediately after maize harvest further reduced nitrate leaching losses in the simulations by 20-30%. The simulations confirmed the benefits of maize cropping systems in reducing nitrate

leaching losses even under high urine N loads compared with *in situ* grazing of winter forage crops.

keywords: winter forage crops, maize silage, kale, swede, fodder beet, biomass yields, excreted urine N, nitrate leaching losses, APSIM, modelling

5.2 Introduction

Nitrogen leaching loss is associated with deteriorating water quality through contaminated groundwater is an important environmental issue in NZ agriculture. Such leaching risks are much more obvious in intensive *in situ* grazing of winter forage crops (e.g. swedes, kale, and fodder beet). Forage brassicas are widely used as winter feed for cattle and sheep on NZ farms, especially in areas with cool winters (Malcolm et al., 2021; Monaghan et al., 2017). The area sown in forage brassicas was estimated to be 236,677 ha in 2017 (Table 2.1) (Statistics NZ, 2017) with about 60,000 ha in fodder beet (Chakwizira et al., 2016a; Ministry for Primary Industries, 2020a). Much of this area is utilised for winter feed, particularly in southern regions. For example, an analysis of satellite imagery revealed that about 13% of the study site (67,618 ha) in Southland was used for grazing winter forage crops (Drewry et al., 2020). The percentage of cropping blocks on farms is generally described from 5% at the national level (Ledgard et al., 2020; Luo & Ledgard, 2021) to less than 20% of the total farm area in the previous report (Monaghan et al., 2013). Although a lower percentage of cropping blocks in the total farm area, research has shown that a 9% of the winter grazed paddocks contributed to the 24% of total N leaching losses in a farm (Chrystal et al., 2012).

Under a typical *in situ* grazing system (Brown et al., 2007; Rugoho et al., 2014), forage brassicas paddocks are usually grazed with a relatively high stocking density (e.g. equivalent to 1000 – 2000 cattle/ha) to ensure maximum feed utilisation (Malcolm et al., 2019; Monaghan et al., 2017; Pleasants et al., 2007). As a consequence, a large amount of urine is deposited in winter grazed paddocks often with several overlapping urine patches, consequently, urine becomes the main source of N leaching from wintering paddocks (de Klein et al., 2010; Romera et al., 2012; Selbie et al., 2015), particularly under high drainage conditions. Muller et al. (2021) defined the N leaching risk as "the function of two factors: occurrence of drainage and N availability in the soil profile at the time of drainage. If either of these factors is zero, N leaching would not occur". Winter grazing systems cannot avoid these two factors – drainage caused by high winter rainfall and N abundance via urine patches on wet soils. In addition to cattle urination, the incorporated left-over crop residue may contribute to the accumulation of residual soil N via mineralisation processes. More importantly, this residual N is rarely taken up by the crops in winter grazing systems due to the 3-5 months fallow period until the establishment of a new crop in spring (Edwards et al., 2014a; Malcolm et al., 2019). This contrasts with a regular pasture grazing system where a part of residual soil N is taken up by the existing pasture from time to time after each grazing period.

Cow urine N is directly related to the crop N consumed by the animals (Dijkstra et al., 2013). About 80-95% of intake N is returned as excreta, mostly in urine (Cichota et al., 2010b). Consequently, the N concentrations of urine patches from dairy cows can range from 500 to 1000 kg N/ha in some cases (Haynes & Williams, 1993; Pleasants et al., 2007). Nitrogen loading via the urine patches is particularly high when the cows are fed with high N forage crops or feed (e.g. forage brassicas). Nitrogen leaching losses from urine patches deposited during grazing of winter forage crops have been reported to range from 50 to 180 kg N/ha (Malcolm et al., 2016a; Monaghan et al., 2013; Shepherd et al., 2012; Smith & Monaghan, 2020; Smith et al., 2012). Therefore, low N forage crops are being assessed as a means of reducing urine N deposition (e.g. Forage for Reduced Nitrate

Leaching programme). We hypothesised that maize is a useful alternative cropping option to *in situ* grazing forage crops because it is a low N forage and is not fed *in situ*. Maize can be planted in much of the North Island and as far south as South Canterbury in the South Island in low altitude areas. There were two objectives in this research:

1. Calculate the total urine N excretion per animal and per hectare based on feeding forage crops of different N content to non-lactating dairy cows using the data from the field trials

2. Quantify the potential nitrate leaching losses from different forage crops under defined scenarios (different N loads deposition and irrigations) using the APSIM model.

5.3 Materials and Methods

The study included two stages. Firstly, excreted urine N (per cow or per ha) was calculated from crop yields and forage N contents using a urinary-N excretion equation. Secondly, these calculated urine N loads were entered into APSIM to predict nitrate leaching losses from five cropping systems (maize, maize-ryegrass, kale, swede, and fodder beet) in the Manawatu environment under long-term simulations from 1991 to 2020. The long-term simulations enable the prediction of more accurate potential nitrate losses from forage crops with the year-to-year variation in climatic conditions.

5.3.1 Field experiments

To calculate cow urine N outputs and urine N loads per hectare, the potentially available feed (assuming 85% utilisation during grazing) and forage N contents from the field trials were utilised in this exercise. Details of the field trials are provided in Chapters 3 and 4. Although field experiments were conducted at Palmerston North, Tokoroa and

Kiwitea, simulations were performed only for the Palmerston North site because the other two sites had limitations of data for modelling exercises, e.g. unavailable forage N analysis at Tokoroa and the limited availability at Kiwitea of soil and weather data which is a detailed requirement of the APSIM model. Therefore, the modelling was only undertaken for the data from the Palmerston North site in 2018/19 and 2019/20.

Briefly, experiments were located at Massey University Dairy in the Pasture and Crop Research Unit (PCRU) on a Manawatu sandy loam soil (Weathered Fluvial Recent soil). In the first season (2018/19), trials included 12 forage entries with two N fertiliser dressings (0, 300 kg N/ha) with the irrigation from January to March (Thant et al., 2020). Yield and forage quality of three cultivars of each species were compared (Chapter 3). In the second season (2019/20), the number of forage entries was reduced to one cultivar each for winter forage crops with consideration of easy management and logistics under multi-environment trials. In addition, it was also feasible to select one superior cultivar each from winter forage crops due to the similarity in yield and feed quality. Therefore, the second season experiments included two maize hybrids and three winter forage crops in each trial. The trials were established under the different managements: irrigated, non-irrigated and late sowing conditions at Massey University, Palmerston North. A total of 200 kg N/ha of urea was applied in three split applications for all trials in 2019/20 (Chapter 4).

5.3.2 Weather data

APSIM requires daily time-step weather data to estimate crop growth and development and soil water dynamics. Long-term daily weather data were obtained from the National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station for the period 1991 to 2020 (Cliflo, 2021). This data provided a daily climate record for rainfall, maximum/minimum temperature, solar radiation, wind, and pan evapotranspiration.

5.3.3 Urine N calculation

Urine N excretion was estimated based on the assumption of feeding forage crops to non-lactating dairy cows, the livestock class mostly grazed on winter forage crops in NZ (Edwards et al., 2020; Edwards et al., 2017). Equations (1) and (2) were used for this urine N estimation (Pacheco et al., 2018; Shepherd et al., 2016).

N surplus (excreta) = N intake in crop – N output in milk [**1**]

Urine N (%) in N surplus = 25.060 + (N concentration of diet (%N) × 12.441) [**2**]

The difference between N intake and N output (e.g. N in milk) was assumed as the N surplus (excreta) (equation 1). However, N output in milk (in equation 1) was assumed to be zero or negligible for a simple calculation in this exercise because no milk is retained in non-lactating cows (Pickering et al., 2020). Nitrogen intake was calculated from a daily dry matter intake (DMI) and forage N contents. Each cow was assumed to have 10 kg daily DMI (eaten) regardless of the forage type, which is expected to meet the energy requirement for a 450–500 kg cow (Nichol et al., 2003). The proportion of urine in the excreta was estimated using the equation of Pacheco et al. (2018) (equation 2). Per cow urine N was extrapolated to total N loads per ha with the potentially available feed from the field experiments (85% of crop yields) in the 2018/19 and 2019/20 seasons (Table 5.4 and Table 5.5).

5.3.4 APSIM model parameterisation

The Agricultural Production Systems sIMulator (APSIM) Next Generation (version 2022.2.7020.0) (Holzworth et al., 2014; Holzworth et al., 2018) was used to simulate the soil-plant-environment interface processes to predict the crop development and nitrate N leaching losses from the respective crop. All crop models are a part of APSIM Next Generation. The full crop model APSIM-Maize and APSIM-Fodder beet were used for maize and fodder beet, respectively (Khaembah et al., 2017; Soufizadeh et al., 2018) while the APSIM-SCRUM (**S**imple **C**rop **R**esource **U**ptake **M**odel) was used to simulate kale and swede crops due to absence of full crop models. The SCRUM model was developed based on the mechanisms and coefficients of the OVERSEER crop model (Cichota et al., 2010a) but allowing dynamic water and N functions in the crop simulations (Khaembah et al., 2015). The default parameterisation in the APSIM release version was maintained except for modifying the biomass removal from and returning to the system as surface organic matter at harvest time. Details of model parameterisation are shown in Table 5.1.

Table 5.1. General management of forage crops used as model inputs in the APSIM.

Crops	**Maize (M) – Ryegrass (RG)**	**Maize**	**Fodder beet**	**Kale**	**Swede**
Urea fertiliser (kg N/ha)					
10 December	100	100	100	100	100
25 January	100	100	100	100	100
Row spacing (mm)	M – 700, RG – 250	700	300	150	150
Plant density (plant/m^2)	M – 12, RG – 1000[b]	12	7	30	20
Sowing date	M – 1 Nov, RG – 1 Apr	1 Nov	1 Nov	1 Nov	1 Nov
Sowing depth (mm)	M – 50, RG – 10	50	30	30	30
Harvest date	M – 25-Mar, RG – 30-Jul	at maturity/ 25-Mar	30-Jul	30-Jul	30-Jul
Remove biomass from the system[a]	M – Default, RG – 80%	Default	80%	80%	80%
Return biomass to the system as surface organic matter[a]	M – Default, RG – 20%	Default	20%	20%	20%
Cultivars	P39G12 (M) and SCRUM-ryegrass year1 (RG)	P39G12	Rivage	SCRUM-kale	SCRUM-fodder beet

[a] Biomass removal and return to the system is simulated to represent the residue left-over after grazing
[b] Ryegrass plant density is estimated based on the literature (Ganeshan et al., 1998; Harris et al., 1996).

Each simulation began on 1 November with the sowing of crops and ended on 31 October of the following year. No cover crops were followed except the maize–ryegrass system, where ryegrass was harvested on 30 July to represent the same duration as the winter forage crops' utilisation. This cropping period and management were selected to represent as much as possible of our field experimentation while following common cropping practices in NZ. To be simple, all crops were sown and harvested on a specific date every year from 1991 to 2020 simulations (Table 5.1). It is also important to note that we have calculated the estimated urine N deposition from the feeding of each specific crop using the N excretion equation, so no animal modules were necessarily brought into the model to avoid duplication of urine deposition. Thus, the potential deposited urine N loads were directly added to the model as an application of urea with an addition of 5 mm of water. In addition, in the real situation, the soil N sources in the grazing system are contributed not only from the cow excreta but also from the crop residues after grazing. To account for this, winter forage crops were simulated as 80% of the harvest removal and 20% of the crop residue returned to the system at every harvest each year. For maize, the residue returned to the system followed the default: 16.7% each of cobs, husks, and stems back to the system every year (Table 5.1).

5.3.5 Management in APSIM crop modelling

Crop modelling was simulated in APSIM under the management of urine N deposition and irrigation levels (Table 5.2). Urine N deposition rates were defined as Control (no urine N loading), Low (lowest urine N loading) and High (maximum urine N loading) N loads based on the calculation of urine N excretion from field trials. Two irrigation levels were 0 and 425 mm irrigated between January and March of the year. The dates of irrigation were based on field experiments with approximately 3-day intervals of irrigation between 10 January and 20 March of the year. Irrigation dates are fixed for all crops every year so they are easier to manage in the long-term simulations.

Table 5.2. APSIM simulation management of urine N deposition (kg N/ha) (Control, Low and High N loads) based on the calculated urine N loads in the 2018/19 and 2019/20 seasons for five cropping options under irrigated (425 mm; irrigated from January to March) and non-irrigated (0 mm) conditions.

Forage crops	**Urine N loads (kg N/ha)**		
	Control	**Low**	**High**
Maize – Ryegrass	0	60	125
Maize	0	60	125
Fodder beet	0	42	132
Kale	0	62	127
Swede	0	47	200
Irrigation levels		0 mm	
(January – March)		425 mm	

5.3.6 APSIM soil parameterisation

The soil properties were taken from the Massey University Dairy No.1, previously determined by Vibart et al. (2015), to parameterise the Soil Water module in APSIM (Table 5.3). The soil data is less than 500 m distance from the trial site, ensuring the most reliable data for this modelling exercise. It is acceptable to use data from similar soils when the data is rare (Cichota et al., 2013; Dann et al., 2006; Webb & Lilburne, 2005). The Soil Water module in APSIM (Probert et al., 1998; Verburg & Bond, 2003) was used to predict soil water and nitrate nitrogen in soils using a daily time step. Whenever necessary, soil crop properties were parameterized following the guideline in the protocol of developing soil descriptions for APSIM (Cichota et al., 2021; Dalgliesh et al., 2016). Soil parameters were also checked with the S-map (Landcare Research, NZ soil database) (https://smap.landcareresearch.co.nz/) and on-site field measurement (0-15 cm depth) to ensure that the properties specified matched those of the trial site.

Table 5.3. Soil properties used in the APSIM simulation.

Depth	Bulk density	Air dry[a]	LL15[b]	DUL[c]	SAT[d]	KS[e]
(cm)	----------------------------		(cm^3/cm^3)		----------------------------	(mm/day)
0-10	1.171	0.05	0.11	0.30	0.43	2015
10-20	1.248	0.12	0.15	0.30	0.47	900
20-30	1.306	0.16	0.16	0.32	0.47	299
30-40	1.344	0.17	0.17	0.31	0.46	267
40-70	1.433	0.07	0.07	0.17	0.38	1312
70-97	1.411	0.06	0.06	0.21	0.38	1609
97-117	1.439	0.08	0.08	0.25	0.37	335
117-131	1.362	0.11	0.11	0.29	0.39	156
131-150	1.375	0.08	0.08	0.24	0.40	408

[a]Soil water content following air drying; [b]Soil water content at 15 bars; [c]Drainage, the upper limit (i.e. field capacity); [d]Saturated water content; [e]Saturated hydraulic conductivity.

5.3.7 Statistical analysis

Statistical analysis followed the field experimentation of simple randomised complete block design (RCB) or factorial arrangement in RCB for urine N excretion per cow or urine N loads per hectare using PROC ANOVA and PROC GLM procedure in SAS software version 9.4 (SAS Institute Inc., Cary NC). The homogeneity of variances (HOV) test was run before analysis using Bartlett's, Brown-Forsythe, and Levene's tests. Means were separated using Fisher's protected least significant difference (LSD) tests when the ANOVA F value was significant ($P < 0.05$). The APSIM simulation outputs are shown as descriptive statistics (average, standard deviation) over a 29-year period from 1991 to 2020.

5.4 Results

5.4.1 Weather data

The climate data for Massey University, Palmerston North from November 1991 to October 2020 are presented in Figure 5.1. Daily global radiation and daily mean temperature data fell into the expected ranges for the Manawatu region and did not exhibit any abnormal recordings. Both radiation and temperature followed the normal seasonal trend of high (from November to March) and low (from April to September) (see Table 3.3, Chapter 3; Figure 4.1 and Figure 4.2, Chapter 4). Rainfall data were also consistent with expectations.

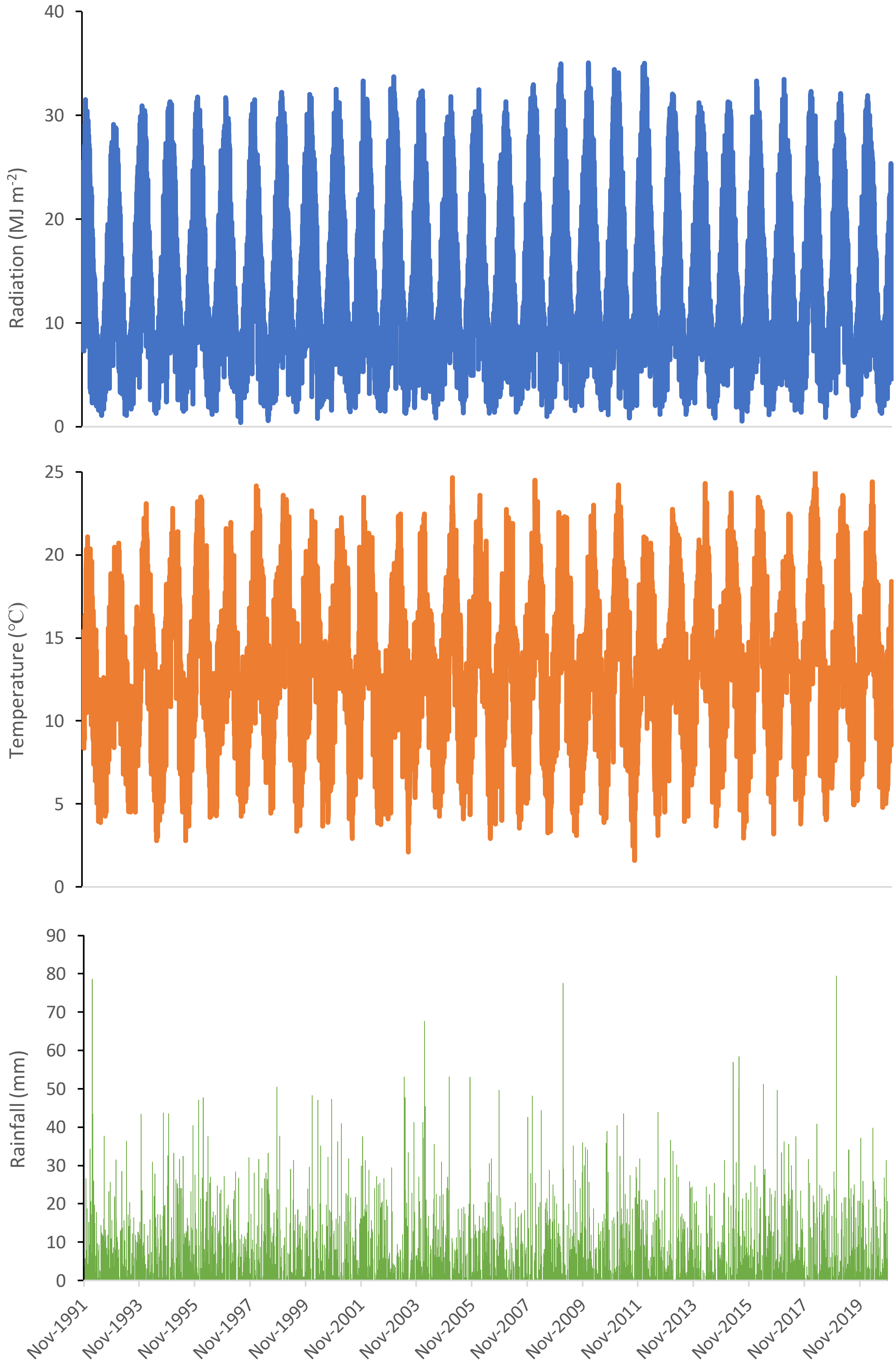

Figure 5.1. Daily radiation (MJ m^{-2}), daily mean temperature (°C) and daily rainfall (mm) at Massey University, Palmerston North, New Zealand from 1 November 1991 to 31 October 2020 (NIWA).

5.4.2 Urine N concentration

Urine N outputs (g N/cow/day) significantly differed from the simulated feeding of different forage crops and nitrogen application treatments in the 2018/19 season (Table 5.4). There was a significant interaction effect of forage crops × nitrogen application on cow urine N excretion. Maize had the lowest N excretion as cow urine, 32.9 g N/cow/day on average, approximately 75% less than the swede crop (average 132.8 g N/cow/day). Similarly, maize was about 50% less in excreted urine N loads per hectare compared with the swede crops (82.5 vs 167.4 kg N/ha). Therefore, the forage N content is still reflected in reducing excreted N loading per hectare basis although there was an influence of yield in the calculation. Kale and fodder beet showed the medium urine N excretion between maize and swede. Furthermore, the higher application of nitrogen can lead to greater excretion of urine N from cows and urine N loads/ha, approximately 31% (62.2 vs 90.2 g N/cow/day) and 39% (90.8 vs 149.6 kg N/ha), respectively.

Table 5.4. Simulated urine N (g N/cow/day) and urine N loads (kg N/ha) at Massey University, New Zealand in 2018/19.

Crop (Forage entry)		Yield	N uptake	Feed[a]	Cows in feeding[b]	Forage N	N intake	Urine N	Urine N loads
		(kg DM/ha)	(kg/ha)	(kg DM/ha)	(no)	(%)	(g/cow/d)	(g/cow/d)	(kg/ha)
Maize	P8000	29,440	280	25024	2502	1.0	94.9	35.0	87.9
	P8805	28,657	258	24359	2436	0.9	90.0	32.8	80.0
	P9400	30,417	262	25855	2586	0.9	86.2	30.9	79.6
Kale	Gruner	21,103	256	17938	1794	1.2	120.1	48.3	87.9
	Regal	16,185	275	13757	1378	1.7	171.8	80.5	109.0
	Sovereign	20,583	327	17495	1750	1.6	157.2	71.9	127.2
Swede	Triumph	17,877	427	15195	1520	2.4	239.3	133.4	201.4
	Clutha Gold	14,035	329	11930	1193	2.3	231.5	127.0	154.4
	Invitation	12,450	305	10583	1058	2.5	245.3	138.1	146.3
Fodder beet	Cerise	20,464	304	17394	1739	1.5	147.6	65.2	114.5
	Enermax	21,518	322	18291	1829	1.5	150.0	67.0	122.0
	Monro	18,182	321	15455	1546	1.8	175.5	84.7	132.3
LSD $_{(0.05)}$		*5,401*	*100*	*4591*	*459*	*0.2*	*22.7*	*16.2*	*43.8*
Nitrogen									
Control (0 kg N/ha)		19,558	250	16624	1662	1.4	140.0	62.2	90.8
High-N (300 kg N/ha)		22,261	361	18922	1892	1.8	178.3	90.2	149.6
LSD $_{(0.05)}$		*2,205*	*41*	*1874*	*187*	*0.1*	*9.3*	*6.6*	*17.9*
Pr>F	Forage entry (En)	***	NS	***	***	***	***	***	***
	Nitrogen (N)	*	***	*	*	***	***	***	***
	En x N	NS	NS	NS	NS	***	***	***	**

[a] Potentially available feed was estimated as 85% of crop yields from experiments; [b] number of cows feeding on 1 ha of specific crop if a daily dry matter intake = 10 kg (eaten); * P < 0.05; ** P < 0.01; *** P < 0.001, NS non-significant

In the 2019/20 season, simulated urine N outputs per cow were significantly affected by forage crops. Overall, swede crops had the highest urine N excretion per cow (88.3-178.0 g N/cow/day) while maize was lowest (39.8-64.3 g N/cow/day) (Table 5.5). On an area basis, maize urine N loads (~120 kg N/ha) were greater than that of other crops (42.2 – 91.0 kg N/ha) in the irrigated trial whereas crops were not significantly different in urine N loads per hectare in MU non-irrigated and MU late trials. Although maize forage N content was lower than other forage crops, total N loads/ha was higher, reflecting the influence of crop yields in the calculation.

Table 5.5. Simulated urine N (g N/cow/day) and urine N load (kg N/ha) at Massey University, New Zealand in 2019/20.

Treatment	Yield (kg DM/ha)	N uptake (kg/ha)	Feed[a] (kg DM/ha)	Cows in feeding[b] (no)	Forage N (%)	N intake (g/cow/d)	Urine N (g/cow/d)	Urine N loads (kg/ha)
Massey University Irrigated								
P8805[†]	26220 a	331 a	22287 a	2229 a	1.3 b	126.8 b	51.9 b	115.0 a
P9400	26792 a	353 a	22773 a	2277 a	1.3 b	131.6 b	54.6 b	124.5 a
Kale	19278 b	257 b	16386 b	1639 b	1.3 b	133.3 b	55.6 b	91.0 b
Swede	12233 c	222 b	10398 c	1040 c	1.8 a	183.0 a	88.3 a	91.1 b
Fodder beet	10186 c	124 c	8658 c	866 c	1.2 b	121.4 b	48.9 b	42.2 c
LSD $_{(0.05)}$	2821.5	38	2398	240	0.3	24.9	16.5	17.9
Pr > F	***	***	***	***	**	**	**	***
Massey University Non-irrigated								
P8805	18061 a	207 a	15352 a	1535 a	1.2 cd	117.2 c	46.9 c	69.9 a
P9400	17864 a	184 ab	15185 a	1519 a	1.1 d	103.6 c	39.8 c	59.9 a
Kale	7210 b	145 bc	6129 b	613 b	2.1 ab	203.3 ab	103.4 ab	62.1 a
Swede	4579 b	102 c	3893 b	389 b	2.3 a	229.2 a	125.5 a	47.1 a
Fodder beet	7264 b	120 c	6174 b	617 b	1.7 bc	166.0 b	76.0 bc	46.6 a
LSD $_{(0.05)}$	3946	47	3355	335	0.5	48.6	37.4	20.7
Pr > F	***	**	***	***	***	***	**	NS
Massey University Late								
P8000	19507 ab	295 a	16581 a	1658 a	1.5 d	147.2 d	64.3 cd	109.6 a
P8805	22662 a	298 a	19263 a	1926 a	1.3 d	131.6 d	54.7 d	103.6 a
Kale	7016 c	180 a	5964 c	596 c	2.6 b	257.8 b	147.7 b	87.3 a
Swede	8286 bc	239 a	7043 bc	704 bc	2.9 a	290.4 a	178.0 a	123.9 a
Fodder beet	13581 b	243 a	11544 b	1154 b	1.8 c	179.8 c	85.6 c	98.1 a
LSD $_{(0.05)}$	5480	95	4658	466	0.3	29.9	23.8	35.4
Pr > F	***	NS	***	***	***	***	***	NS

[a] Potentially available feed was estimated as 85% of crop yields from field experiments; [b] number of cows feeding on 1 ha of specific crop if daily dry matter intake = 10 kg (eaten); * P < 0.05; ** P < 0.01; *** P < 0.001, NS non-significant

5.4.3 Simulated biomass yields

Average simulated forage yields over 29 years (1991 – 2020) are shown in Figure 5.2. Simulated yields for maize–ryegrass, maize, fodder beet, kale and swede were 22850 – 27146, 22183 – 24186, 22814 – 22815, 15914 – 16636, 14175 – 15089 kg DM/ha under irrigation and 20699 – 24467, 19451 – 20528, 21466 – 21468, 11717 – 12201, 11581 – 11891 kg DM/ha under non-irrigation, respectively. Maize monocrop or maize–ryegrass double cropping gave a higher yield than forage brassicas (kale and swede) in all scenarios but did not differ from fodder beet. In general, irrigation increased yields of all forage crops, but a significant difference was only observed in kale and swede crops, with approximately 26% and 20% increase in yield by irrigation in all scenarios, respectively. Crop yields did not differ between three urine N deposition rates (Figure 5.2), although the yield increased slightly with a relative increase in urine N deposition rates. This is expected because N sources from urine occurred at the end of the cropping season, and assuming much of this N will be lost through mineralisation processes before the beginning of the next cropping season.

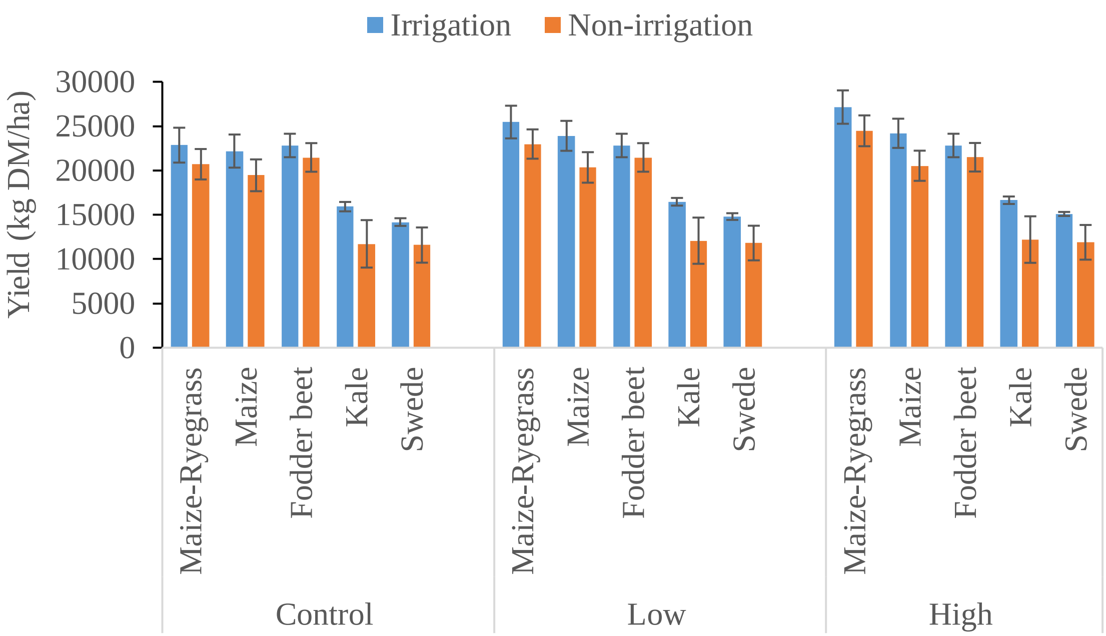

Figure 5.2. Average simulated forage yields under the scenarios of irrigation/non-irrigation and three urine N loads (Control, Low and High) at Massey University, New Zealand over 29 years from 1991 to 2020.

5.4.4 Simulated nitrogen (N) uptake

Crop N uptake (kg/ha) was checked in the simulations to assess the subsequent effect on nitrate leaching losses from each forage crop. Higher simulated crop yields were likely to relate to higher N uptake of forage crops (Figure 5.2 and Figure 5.3). For example, high yields of maize and fodder beet were related to the N uptake above 250 kg N/ha compared to about <140 or ~170 kg/ha of N uptake by kale crops in non-irrigated and irrigated treatments. Kale crop N uptake was the lowest among the crops, indicating high risks of potential N leaching from the soil N left-over after the harvest. In contrast, fodder beet showed higher N uptake with the proportional increase of urine N deposition under non-irrigated conditions.

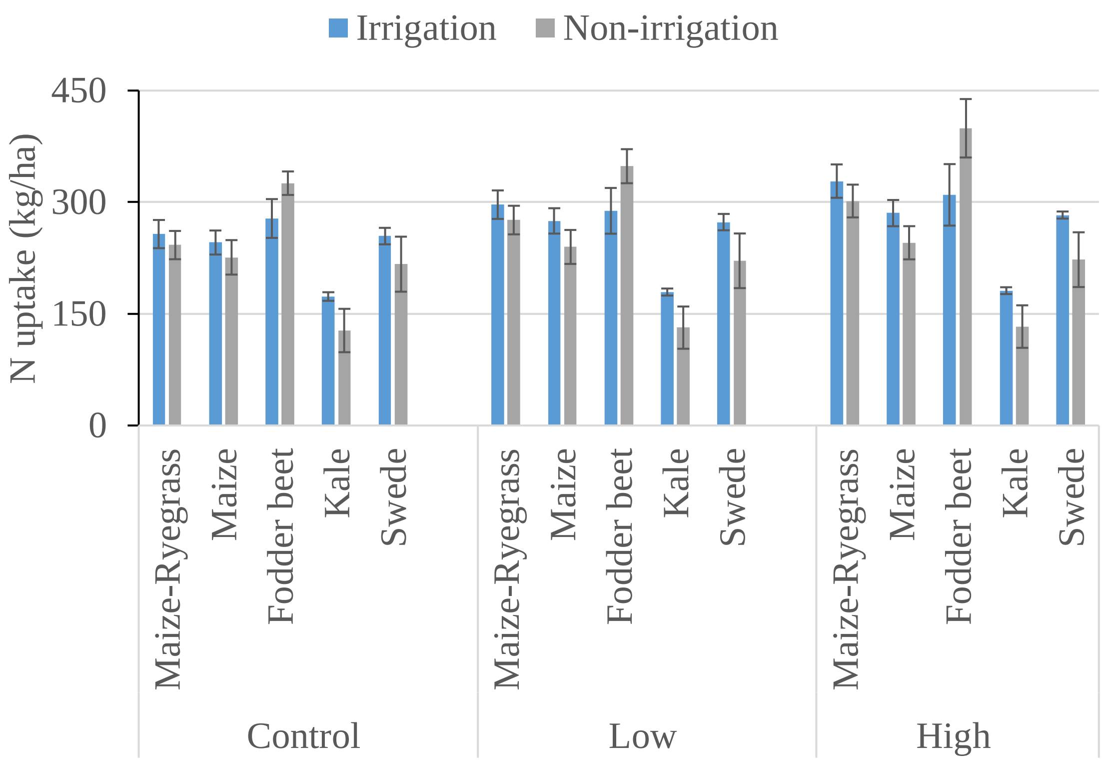

Figure 5.3. Average simulated nitrogen uptake (kg N/ha) of forage crops under the scenarios of irrigation/non-irrigation and three urine N loads (Control, Low and High) at Massey University, New Zealand over 29 years from 1991 to 2020.

5.4.5 Simulated nitrate leaching losses

Overall, nitrate leaching losses from forage crops ranged from 21 to 201 kg N/ha on average across all scenarios of long-term simulations (Figure 5.4). Across three defined N loads scenarios, predicted N leaching losses for maize–ryegrass, maize, fodder beet, kale and swede were 26-84, 32-120, 18-72, 106-201, 48-199 kg N/ha under non-irrigated conditions and 21-68, 21-94, 46-126, 69-162, 20-154 kg N/ha under irrigated conditions, respectively. Nitrate leaching losses were higher under high urine N loads simulations compared to control and low urine N loads. The model indicated the higher urine N deposition at the end of the crop cycle, the greater in predicted nitrate leaching risks (Figure 5.4).

Greater biomass yield (Figure 5.2) and higher uptake of N (Figure 5.3) significantly reduced nitrate leaching losses (e.g. maize and fodder beet) (Figure 5.4). Similarly, the irrigated treatment generally reduced predicted N leaching losses compared with non-irrigated due to the possible effect of irrigation to higher yield and increase N uptake by the crops under irrigation. However, the higher N uptake by fodder beet in non-irrigated conditions (Figure 5.3) considerably reduced nitrate leaching losses (about 50%) compared with the irrigated treatments (Figure 5.4). It should be noted that all crops showed a wide range of nitrate leaching losses under the non-irrigated conditions, particularly when the high urine N loading was run in the simulation.

The cover crop (ryegrass) sown after maize reduced nitrate leaching losses to a considerable amount compared with maize monocrop, for example, 26 vs 32, 50 vs 72, 84 vs 120 kg N/ha under non-irrigated conditions and 21 vs 21, 38 vs 50, 68 vs 94 kg N/ha under irrigated conditions in control, low and high urine N loads, respectively. However, the statistical difference did not observe in nitrate losses between maize and maize-ryegrass systems. At least, this indicated the beneficial effect of ryegrass cover crop taking up residual soil N during winter, minimising losses.

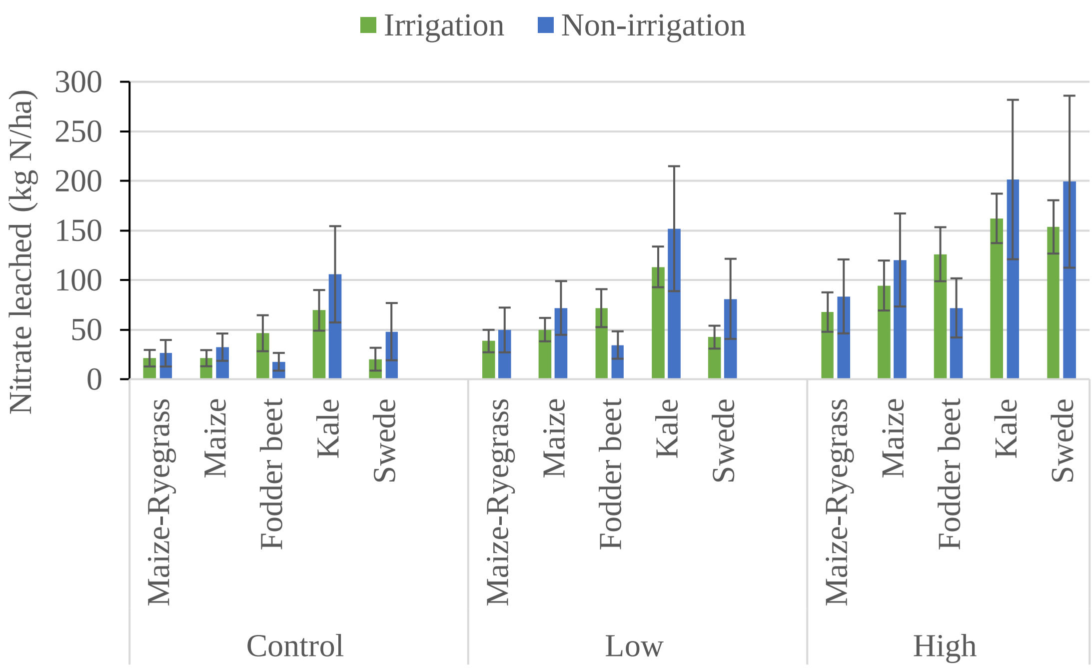

Figure 5.4. Average simulated nitrate leaching losses (kg N/ha) from forage crops under different urine N loads (Control, Low and High) for irrigated and non-irrigated crops at Massey University, Palmerston North, New Zealand over 29 years from 1991 to 2020.

5.5 Discussion

5.5.1 Excreted urine N

When feeding different forage crops to a non-lactating dairy cow on a 10 kg DMI, urine N excretion is entirely related to forage N content. Urine N output per cow ranged from 30.9 to 178.0 g N/cow/day depending on the forage N content of crops. Consequently, the calculation highlighted the potential of low N forage crops in reducing urine N excretion. For example, based on daily DMI, maize and fodder beet were lower in urine N excretion per cow basis compared to forage brassicas in both seasons, confirming the potential to reduce urinary N excretion.

On an area basis, the differences in urine N loads per hectare between crops become smaller due to the higher production of maize and lower production of forage brassicas and fodder beet (e.g. Table 5.5). This indicates the influence of crop yields in the calculation. At the same time, it is important to note that the higher production per unit area will have more available feed and economic benefits. For example, maize produced a greater yield, so can feed higher numbers of cows per season from each ha (3-4 times greater) (Table 5.4 and Table 5.5).

5.5.2 Predicted biomass yields and N uptake

The APSIM simulations of biomass yield and N uptake were consistent with field estimates, giving confidence on the estimation of nitrate leaching losses from forage crops. Predicted biomass yields and N uptake generally fell into the range observed by field experimentations in 2018/19 but slightly to moderate variations compared with the results from the 2019/20 season (Table 5.4 and Table 5.5). However, this is not unexpected because crop cultivars differed and simulations are fixed for some parameters (e.g., harvesting, fertiliser application, and irrigation) year-to-year for the long-term simulations. Comparison between field observation and model outputs was primarily to ensure a reliable data range rather than to test the model's accuracy in this study.

5.5.3 Nitrate losses under irrigated and non-irrigated treatments

In the comparison of irrigated and non-irrigated simulations (Figure 5.4), leaching losses are slightly lower under irrigated conditions. Nitrogen leaching may increase with the irrigation due to higher drainage in general. However, the risk of drainage after summer irrigation (from January to March) is low due to lower rainfall, higher evapotranspiration and higher soil moisture deficit in the summer compared to other seasons. Therefore, it is likely that the soil could hold more water and the crop water demand in summer will be higher than in other seasons, resulting in increased water use efficiency and subsequently reduced drainage and leaching (Muller et al., 2021). On the other hand, irrigation can enhance N use efficiency, meaning higher biomass may uptake more N over summer (the general trend observed in this study), leaving less N to be leached during winter (Vibart et al., 2015). In addition, irrigated soil may decrease soil temperature. Lower soil temperature (<5 °C) influences the number of ammonia oxidizing bacteria (AOB; primarily responsible for the conversion of ammonium into nitrate, i.e. nitrification), thereby resulting in the low nitrate leaching losses (Carey et al., 2018). Some research has highlighted that irrigation could mitigate and reduce a certain amount of the nitrate leaching losses depending on soil types (Bright et al., 2019; Muller et al., 2021; Vogeler et al., 2019).

5.5.4 Effect of a cover crop on nitrate losses

The cover crop (ryegrass) sown after maize reduced nitrate leaching by approximately 20-30% on average across different N loads (Figure 5.4), highlighting effectiveness of cover crops in reducing N leaching losses (Malcolm et al., 2020; Michel et al., 2022; Teixeira et al., 2015; Teixeira et al., 2016; Teixeira et al., 2021; Tsimba et al., 2020; Tsimba et al., 2022; Zyskowski et al., 2016). Nitrogen leaching reduction under the ryegrass cover crop in this simulation is lower than those observed by Zyskowski et al. (2016), who found that an April sown triticale cover crop reduced N leaching by about 60% compared with fallow. The different cover crops in our simulations with different N loading rates and earlier harvest of ryegrass (30 July compared to 15 September) probably explain the difference. However, the average predicted maize yields in this study were similar to their simulations (23 t DM/ha).

5.5.5 Predicted nitrate losses

Overall, the model prediction was useful for quantifying the N leaching risks of forage crops. Predicted leaching losses from winter forage crops were notably higher than pasture systems in the Manawatu region (~50 kg N/ha) (Hanly et al., 2018; Parminter et al., 2019a; Parminter et al., 2019b) due to possible differences in management practices and urine N deposition. The mean annual nitrate leaching losses of maize monocrop under high N loads (94-120 kg N/ha) were generally similar to the leaching losses (70-98 kg N/ha) observed by Teixeira et al. (2016) and leaching under medium N load (104-128 kg N/ha) observed by Zyskowski et al. (2016). Furthermore, maize nitrate losses from the lower urine N loads were similar to recent field measurements in Waikato (Tsimba et al., 2022). However, the overall maize nitrate losses are considerably lower than losses from simulated under heavy N loads in Waikato (148-187 kg N/ha) by Zyskowski et al. (2016) (240 kg N/ha from fertiliser + 190 kg N/ha from N loads in soil). Similarly, nitrate leaching losses from high urine N scenarios in kale (162-201 kg N/ha) and fodder beet (72-126 kg N/ha) were consistent with previous research (Malcolm et al., 2019; Smith & Monaghan, 2020). Low N content crops, maize and fodder beet proved the most promising in reducing the urinary N excretion and consequently reduced nitrate leaching losses with the achievement of high yield potential. Although fodder beet and maize have comparable nitrate leaching losses, it should be highlighted that maize has some advantages. The use of cover crops and flexible feeding systems (such as feeding in a portable pad and barn system, stand-off areas) will possibly further reduce nitrate leaching losses under maize compared with greenfeed wintering systems (Beukes et al., 2011a; Chrystal, 2017).

5.6 Conclusion

Low N forage crops resulted in lower urine N excretion based on a 10 kg daily dry matter intake in non-lactating dairy cows. Per cow urine N excretion (g N/cow/day) was lowest for maize in comparison with winter forage crops (kale, swede, and fodder beet) but per area N loads (kg N/ha) varied due to the influence of crop yields. The model predicted that maize and fodder beet produced lower nitrate leaching losses compared with brassica crops (kale and swede) under different scenarios. Maize – ryegrass cropping system further reduced nitrate leaching losses and produced the greatest combined biomass yields, confirming the benefits of a cover crop, both economic and environment. Higher urine N loads produced higher nitrate leaching losses, indicating the urine N deposition at the end of the crop season influenced the total nitrate losses. This highlighted the opportunity to use different cropping systems to reduce urine N deposition and minimize nitrate leaching losses. Although this initial modelling exercise can quantify potential nitrate leaching losses from each crop, further research is still required to validate the model accuracy as well as the adaptability and cost-benefits of each cropping system over a wider range of environments in NZ.

5.7 Acknowledgements

We would like to express our sincere thanks to Dr Ronaldo Vibart (AgResearch) and co-authors for permitting us to use their published soil properties for the APSIM modelling in this study. We would like to acknowledge Dr Edith Khaembah (Plant and Food Research) and Fernando Avendano Veas (PhD student) for their assistance and support in the technical skills of the APSIM model parameterisation.

5.8 Supplementary materials

Table S 5.1. A summary of average values of urine N per cow and urine N loads per hectare of forage crops in 2018/19.

Crops	Urine N (g N/cow/day)	Urine N loads (kg N/ha)
Maize	32.9	82.5
Kale	66.9	108.0
Swede	132.8	167.4
Fodder beet	72.3	122.4
LSD $_{(0.05)}$	**16.2**	**43.8**
Control (0 kg N/ha)	62.2	90.8
High-N (300 kg N/ha)	90.2	149.6
Difference between N application	**(31%)**	**(39%)**

Table S 5.2. Simulated biomass yield (t DM/ha) (mean, standard deviation, minimum and maximum) of forage crops in APSIM grown in the years 1991 – 2020 at Massey University, New Zealand. ⸸ Maize + Ryegrass yield (t DM/ha).

Irrigation (mm)	Urine N (kg N/ha)	Forage crops	Biomass yield (t DM/ha)			
			mean	sd	min	max
Non-irrigated (0 mm)	Control	Maize – Ryegrass	20.7 (19.6+1.1)[⸸]	1.7	17.1	24.0
		Maize	19.4	1.8	15.6	23.0
		Fodder beet	21.5	1.6	16.5	24.0
		Kale	11.7	2.7	6.9	16.6
		Swede	11.6	1.9	7.7	14.9
	Low	Maize – Ryegrass	23.0 (20.2+2.8)	1.7	19.6	26.6
		Maize	20.3	1.7	16.9	24.7
		Fodder beet	21.5	1.6	16.5	24.0
		Kale	12.1	2.6	7.2	16.6
		Swede	11.8	1.9	7.9	14.9
	High	Maize – Ryegrass	24.5 (20.3+4.2)	1.7	20.7	27.8
		Maize	20.5	1.7	17.2	24.8
		Fodder beet	21.5	1.6	16.5	24.0
		Kale	12.2	2.6	7.3	16.6
		Swede	11.9	1.9	8.0	14.9
Irrigated (425 mm)	Control	Maize – Ryegrass	22.9 (22.8+0.1)	1.9	17.7	26.4
		Maize	22.2	1.8	18.4	25.9
		Fodder beet	22.8	1.3	19.4	25.2
		Kale	15.9	0.5	14.0	16.6
		Swede	14.2	0.4	12.9	14.9
	Low	Maize – Ryegrass	25.4 (23.8+1.6)	1.8	21.1	28.9
		Maize	23.9	1.7	20.4	27.4
		Fodder beet	22.8	1.3	19.4	25.2
		Kale	16.5	0.4	14.8	17.1
		Swede	14.8	0.4	13.5	15.2
	High	Maize – Ryegrass	27.1 (24.0+3.1)	1.9	23.3	30.8
		Maize	24.2	1.6	20.4	27.3
		Fodder beet	22.8	1.3	19.4	25.2
		Kale	16.6	0.4	15.1	17.1
		Swede	15.1	0.2	14.5	15.3

Table S 5.3. Simulated crop N uptake (kg N/ha) (mean, standard deviation, minimum and maximum) of forage crops in APSIM grown in the years 1991 – 2020 at Massey University, New Zealand. ⱡ Maize + Ryegrass N uptake (kg N/ha).

Irrigation (mm)	Urine N (kg N/ha)	Forage crops	N uptake (kg N/ha)			
			mean	sd	min	max
Non-irrigated (0 mm)	Control	Maize – Ryegrass	242 (228+14)[ⱡ]	19	201	280
		Maize	226	23	186	271
		Fodder beet	326	16	294	364
		Kale	128	29	75	181
		Swede	217	37	144	280
	Low	Maize – Ryegrass	276 (237+39)	19	239	311
		Maize	240	23	198	283
		Fodder beet	348	23	305	406
		Kale	131	28	78	181
		Swede	221	37	148	280
	High	Maize – Ryegrass	302 (241+61)	22	261	337
		Maize	246	22	202	295
		Fodder beet	399	39	320	478
		Kale	133	29	79	181
		Swede	223	37	149	280
Irrigated (425 mm)	Control	Maize – Ryegrass	257 (256+1)	19	194	288
		Maize	246	16	205	276
		Fodder beet	278	26	220	321
		Kale	173	6	152	180
		Swede	254	11	231	273
	Low	Maize – Ryegrass	297 (276+21)	19	238	328
		Maize	275	17	238	310
		Fodder beet	288	31	220	333
		Kale	179	5	161	186
		Swede	273	11	249	286
	High	Maize – Ryegrass	328 (284+44)	22	272	369
		Maize	285	18	253	324
		Fodder beet	310	41	220	368
		Kale	181	5	164	186
		Swede	283	5	268	286

Table S 5.4. Simulated soil N content (kg N/ha) (mean, standard deviation, minimum and maximum) in APSIM grown in the years 1991 – 2020 at Massey University, New Zealand.

Irrigation (mm)	Urine N (kg N/ha)	Forage crops	Soil N content (kg N/ha)			
			mean	sd	min	max
Non-irrigated (0 mm)	Control	Maize – Ryegrass	219	60	72	288
		Maize	200	51	72	266
		Fodder beet	285	47	138	373
		Kale	178	28	108	238
		Swede	222	24	143	271
	Low	Maize – Ryegrass	238	67	72	327
		Maize	217	53	75	293
		Fodder beet	292	50	138	387
		Kale	169	18	116	207
		Swede	222	24	143	271
	High	Maize – Ryegrass	249	71	71	347
		Maize	225	54	78	303
		Fodder beet	317	58	138	417
		Kale	169	18	116	207
		Swede	222	24	143	272
Irrigated (425 mm)	Control	Maize – Ryegrass	117	27	59	158
		Maize	110	24	58	151
		Fodder beet	151	18	104	193
		Kale	109	16	82	149
		Swede	134	12	112	165
	Low	Maize – Ryegrass	132	33	58	181
		Maize	120	28	60	161
		Fodder beet	152	18	104	196
		Kale	102	11	81	132
		Swede	137	13	113	170
	High	Maize – Ryegrass	141	37	57	201
		Maize	127	30	60	179
		Fodder beet	157	19	104	204
		Kale	102	11	80	132
		Swede	139	13	116	173

Table S 5.5. Simulated N leaching losses (kg N/ha) (mean, standard deviation, minimum and maximum) of forage crops in APSIM grown in the years 1991 – 2020 at Massey University, New Zealand.

Irrigation (mm)	Urine N (kg N/ha)	Forage crops	N leached (kg N/ha)			
			mean	sd	min	max
Non-irrigated (0 mm)	Control	Maize – Ryegrass	26	13	10	72
		Maize	32	14	12	82
		Fodder beet	18	9	8	53
		Kale	106	49	25	235
		Swede	48	28	7	136
	Low	Maize – Ryegrass	50	23	17	106
		Maize	72	27	29	152
		Fodder beet	34	14	15	83
		Kale	152	63	47	317
		Swede	81	40	22	207
	High	Maize – Ryegrass	84	37	30	194
		Maize	120	47	53	259
		Fodder beet	72	30	32	155
		Kale	201	80	71	410
		Swede	199	87	57	442
Irrigated (425 mm)	Control	Maize – Ryegrass	21	8	15	60
		Maize	21	8	16	61
		Fodder beet	46	18	22	111
		Kale	69	21	39	144
		Swede	20	12	8	71
	Low	Maize – Ryegrass	38	11	21	66
		Maize	50	12	31	80
		Fodder beet	72	19	41	118
		Kale	113	21	79	166
		Swede	42	12	24	72
	High	Maize – Ryegrass	68	20	34	113
		Maize	94	25	54	143
		Fodder beet	126	27	80	192
		Kale	162	25	125	233
		Swede	154	27	73	224

Chapter 6 General Discussion and Conclusion

6.1 Introduction

New Zealand's farming systems are mainly based on the perennial ryegrass-white clover pastures (Chapman et al., 2017; Waghorn & Clark, 2004) with supplementary feeding from home-grown feed crops during a feed shortage in summer or winter periods (Pinxterhuis et al., 2015). Several annual forage species such as cereals, legumes, herbs, plantain, beets, and forage brassicas are utilized for this purpose (Havilah, 2011; Westwood, 2021). However, traditional winter forage crops, like forage brassicas and fodder beet, are associated with *in situ* grazing practices, particularly during winter. This intensive grazing results in soil degradation and nutrient losses to waterways, resulting in nitrate contamination. Alternative cropping options may be able to minimise the problems associated with traditional winter forage grazing systems.

For better farm production and management, the cropping option must be not only environmentally beneficial but also economically viable. From an economic point of view, increased crop yields and good forage quality are essential for production of milk and meat. Thus, the alternative cropping option must have a competitive yield and adequate feed quality as well as reduced N losses compared to winter forage crops. The aim of this study was to determine whether maize silage offers a viable alternative to winter forage crops (kale, swede, and fodder beet) grazed *in situ* with the following objectives:

1. to quantify total DM yield and nutritive values of maize silage and traditional winter forage crops in a range of environments in NZ
2. to investigate the growth and development of different forage crops
3. to identify site and forage species interactions for yield and forage quality

4. to assess potential nitrate leaching losses resulting from different forage cropping systems

6.2 The benefits of high yields

A series of experiments including maize silage and winter forage crops (a total of six trials) was established in a range of environments in the North Island in the 2018/19 and 2019/20 seasons. Trial details can be seen in Chapters 3 and 4. The trial sites represent most of the areas that are grown to maize and winter forage crops in the North Island. Even though winter forage crops are widely sown in the South Island, the region was not included in the study due to the logistics and time limitations.

Over the two years (2018/19 and 2019/20), winter forage crop performance varied depending on the locations, management practices, and seasonal variations. Although the maximum potential yield was achieved in winter forage crops at Palmerston North with irrigation and a high dose of N fertiliser, there was also a complete loss of some crops due primarily to dry conditions and competition from weeds (e.g. fodder beet at Tokoroa, Chapter 3). Fodder beet is susceptible to weeds and dry conditions, particularly in the early stage because the growth is slow, taking about 120 days from sowing to reach a LAI of 3. However, a weed-free environment enhances leaf canopy development and greater LAI in fodder beet (Figure 4.4, Chapter 4). Thus, precision sowing and good weed control are recommended due to its long establishment time with relatively low population density (Matthew et al., 2011). Compared with fodder beet, kale and swede were more tolerant to dry weather conditions, resulting in a reasonable growth recovery during later stages as water or rainfall became available (Plate 4.1, Chapter 4).

In this study the yield of the winter crops ranged from 4579 – 21341, 7016 – 22928, 7020 – 21518 kg DM/ha for swede, kale, and fodder beet, respectively, over the two years of experimentations (Chapters 3 and 4). The wider yield range and a higher probability of crop failure for winter forage crops could result in unreliable feed supply. This would further elevate the shortage of on-farm feed which could result in reduced milk production unless an alternative management option is considered or scheduled.

This study has demonstrated greater maize silage yield potential compared with winter forage crops. The lowest maize yield (10940 kg DM/ha) was obtained at Kiwitea (Chapter 4) while the highest yield (30417 kg DM/ha) was obtained at Palmerston North (Chapter 3). The latter received irrigation and high N fertiliser (300 kg N/ha). Median yield levels of 17000 kg DM/ha were obtained at Tokoroa under rainfed conditions with high N fertiliser (300 kg N/ha) (Chapter 3). Despite the lower maize yields at Kiwitea and Tokoroa, maize could be considered competitive relative to other crops in this study.

The highest maize yield of 30417 kg DM/ha (see section 3.4.5, Chapter 3) was probably due to its response to irrigation in comparison with the average 17000 kg DM/ha maize yields at Tokoroa while the brassica yields were similar at both sites in 2018/19. The cover crop (Italian ryegrass cv. Lush) after maize harvest gave a further yield of 2600 kg DM/ha on average. It is important to note that Italian ryegrass was harvested in June (3 months duration), hence the maize silage options only consider partial rather than a whole annual crop sequence yield over 12 months.

The maize yield achieved in the Massey University trials over 5 months is high although a high inputs of fertiliser and irrigation were required. If maize is followed by cereals, e.g. oats or triticale producing 10 t DM/ha (Chakwizira et al., 2017b; de Ruiter et al., 2009a; Fletcher et al., 2011; Minnée et al., 2009), an annual total yield of ~40 t DM/ha is achievable. This is about 90% of the NZ pastoral industries' goal of 45 t DM/ha annually (de Ruiter et al., 2009a). A total sequence yield of 48.9 t DM/ha from maize (33 t DM/ha) + Oats (15.9 t DM/ha) has been achieved in Waikato with irrigation, high N fertiliser, and long maturing hybrids (CRM 113) (Minnée et al., 2009). This suggests that ‘maize silage’ is one of the most promising crops for attaining highest forage yields. Although competitive, the lower yields at Kiwitea where the marginal conditions for maize in terms of climate and paddock condition should be taken into consideration when substituting maize for winter forage crops.

6.2.1 Comparison of production costs

Maize growing and harvest costs are estimated at $4125/ha in average fertility soil and $3240/ha in high fertility soil (Genetic Technologies, 2022). The main difference is increased lime and fertiliser costs for low fertility soils. Of the total production cost, harvesting and stacking and silage inoculation is about 39-50% of the total cost. Winter forage crops do not incur these costs. Thus, maize is generally considered a high input crop compared to winter forage crops. However, raising the yield means the cost of production goes down per dry matter or energy basis (c/kg DM or c/MJME).

The cost per dry matter or energy basis is presented for each crop in Table 6.1, with recent industry production costs and actual yields (lowest, average, and highest) achieved in this study. In general, production cost for maize ($3240 or $4125/ha) is about 2-3 times higher than kale ($2150/ha) and swede ($1400/ha) crops. On a dry matter and energy basis, maize unit costs are similar to fodder beet which is also a high input crop. Maize unit costs are slightly greater than kale and swede on both dry matter and energy basis in all yield ranges but similar to kale and swede crops at the low input requirement.

The simple cost analysis highlighted that maize has more benefits for many reasons. It is important to note that kale and swede will require more land areas to be equivalent to the total yield production from maize. In addition, a cover crop can be established immediately after maize and consequently, the total annual yield from double cropping will certainly be greater than that of winter forage crops, with the evidence from the additional yield of Italian ryegrass in Chapters 3 and 4. In contrast, winter forage crops require approximately 3-5 months to sow a cover crop after grazing, meaning an additional yield from a cover crop within a year is uncertain since winter forage crop duration lasts for 8-9 months. Hence, it is suggested that the simple economic analysis favours maize as an alternative option to winter forage crops if farmers consider switching to a cropping system. However, it is recommended that farmers should consider maize sowing on a fertile paddock to have an average yield potential and reduced costs of fertiliser.

On the other hand, the WFC, particularly swede, showed cost-effectiveness both per kg dry matter and on an energy basis compared with maize if swede yield was above 11,600 kg DM/ha (Table 6.1). In this research, the results from the Kiwitea trial are a good example of this cost-effectiveness related to similar yields between maize and swede (Chapter 4). This is mainly due to a high production cost of maize particularly the harvesting cost compared to swede, which is grazed *in situ*. Maize yield lower than an average of 20,000 kg DM/ha will reasonably increase the cost. Therefore, it should be considered for cost-effectiveness whether maize could be reliably grown or not especially in regions where summer rainfall is less reliable and on farms without irrigation. In addition, paddock selection (e.g., effluent paddocks), the timing of maize sowing to give a time for planting of succeeding crop after maize harvest are important to compensate the maize production cost compared with WFC.

Table 6.1. Production costs of forage crops based on industry production cost and current research forage yield potential.

	Production cost ($/ha)	Yield[a] (kg DM/ha)	Energy[b] (MJ/kg DM)	Cost (c/kg DM)	Cost (c/MJME)
Maize	$4125 (Genetic Technologies, 2022)	11,000	9.9	37.5	3.7
		20,733	11.4	19.9	1.7
		30,400	12.2	13.5	1.1
	$3240 (Genetic Technologies, 2022)	11,000	9.9	29.5	3.0
		20,733	11.4	15.6	1.4
		30,400	12.2	10.7	0.9
Fodder beet	$3000 (Anon., 2021)	7,000	10.8	42.9	4.0
		11,621	14.0	25.8	1.8
		21,500	14.9	14.0	0.9
Kale	~$2150 (DairyNZ, 2015; Owlfarm, 2021)	7,000	8.9	30.7	3.5
		13,933	11.7	15.4	1.3
		22,900	12.7	9.4	0.7
Swede	$1400 (PGG Wrightson Seeds, 2020)	4,600	10.1	30.4	3.0
		11,603	13.5	12.1	0.9
		21,300	14.5	6.6	0.5

[a] Low, average, and high crop yields from field experiments in 2018/19 and 2019/20

[b] Low, average, and high metabolisable energy values from field experiments in 2018/19 and 2019/20

6.3 Assessment of feed quality of forage crops

While dry matter yield remains a key factor in crop production and economic benefits, the nutritive quality of forage crops should be adequate to animal requirements. Energy, protein, and fibre sources are considered important feed quality attributes for animal performance and health.

Metabolisable energy (ME) is accepted as the best overall measure of feed quality (White et al., 1999), and the most common indicator of feeding value in NZ farm systems (Waghorn, 2007; Waghorn & Clark, 2004). Since metabolisable energy is used for animal maintenance and production (Baldwin, 1995), it is a useful indicator to assess animal performance. In general, forage ME values are described as excellent (>11.0 MJ ME/kg DM), acceptable (>9 MJ ME/kg DM), and poor quality (<9 MJ ME/kg DM) (de Ruiter et al., 2007). The higher energy content of forage crops will be the greater value of feed for animals. All forage crops in the current study showed a good profile of ME values across all experiments conducted in the 2018/19 and 2019/20 seasons except kale samples in the first season (<9 MJ/kg DM). Swede and fodder beet had higher ME values (~10.0 – 14.9 MJ/kg DM) than maize and kale (~9.0 – 12.7 MJ/kg DM) over the two years. The higher ME content of swede and fodder beet reflects greater feed digestibility because the higher ME values generally indicate a high digestibility and rapid passage (Waghorn, 2007).

While swede and fodder beet are higher in forage ME values, maize produces the highest energy yield per hectare (GJ/ha) (ME yield = Biomass yield/ha × forage ME) across all experiments over the two years except at Kiwitea, where maize energy yields are similar to other crops (Table 6.2). The energy from maize silage per unit area was 2-3 times higher than that of other crops in each trial. The moderate ME value of maize, together with its high yield means that maize is the best energy-rich crop. In addition, maize is suitable for filling energy deficits at any time of the year since it is feasible to store whereas grazing-type winter crops need to be fed at their peak of yield and quality whether the time is the highest feed demand by cows or not.

Table 6.2. The total energy yield (GJ/ha) of forage crops in New Zealand over the two years (2018/19 and 2019/20).

	Metabolisable energy yield (GJ/ ha)				
	2018/19[a]	2019/20[b]			
	MU	MUI	MUNI	MUL	KL
Maize	316	291	200	276	130
Kale	176	216	89	91	150
Swede	151	174	65	117	169
Fodder beet	217	152	34	201	105

MU= Massey University, MUI = Massey University Irrigated trial, MUNI = Massey University Non-irrigated trial, MUL =Massey University late trial, KL = Kiwitea late trial
[a] mean of three cultivars in the first season
[b] P8805 maize hybrid data is used in the 2019/20 season since it is common at all sites

Metabolisable energy values were not affected by management practices, such as fertiliser N application or site differences managed in this research. However, feed quality (ME and CP particularly) of crops was comparatively less in the first season (2018/19) than in the second season (2019/20) (Chapters 3 and 4). This could potentially have been a result of the sample oven drying method used in the first season. The drying method could influence feed quality values since high drying temperature could reduce chemical composition and digestibility (Deinum & Maassen, 1994).

Crude protein (CP) is another principal feed component affecting feeding value (Waghorn, 2007), requirements are 10-16% for non-lactating and >16% for lactating cows (Dalley et al., 2017). In this study, only kale and swede, (mean 14-15% CP) were adequate for maintenance feeding whereas maize and fodder beet were <10% CP. However, the lower CP content in maize and fodder beet may be an advantage in minimising N leaching losses. Dalley et al. (2017) defined the desirable feed quality traits for good environmental outcomes as <12% CP and >30% soluble sugars and starch (SSS). Maize and fodder beet are suitable supplements for the NZ farming systems because perennial ryegrass-white clover pastures usually constitute >11.5 MJ ME/kg DM and up to 30% CP (Dalley & Gardner, 2012; Dalley & Geddes, 2012; Waghorn et al., 2007; Waghorn & Wilson, 1974). This means the protein is usually greater than animal requirements in pasture systems. In addition, ruminants can adapt to the low CP forage because they can get nitrogen as urea from the bloodstream back to the rumen, primarily through the saliva (Waghorn & Clark, 2004).

The minimum requirement for SSS would be described as >30% (Dalley et al., 2017; Dalley et al., 2020b) for the cow's requirements and environmental outcome while the optimum values are also stated as between 36 – 44% (National Research Council, 2001; Nichol et al., 2003). Maize is the only fit in this range whereas fodder beet is higher, and forage brassicas are generally below the optimum SSS range.

Acid detergent fibre (ADF) and neutral detergent fibre (NDF) concentrations are typically defined as >21% and >33% for the optimum rumen function (National Research Council, 2001; Nichol et al., 2003). Maize and kale have comparatively adequate fibre sources for the optimum rumen function (>21% ADF and >33% NDF) while swede and fodder beet are lower in fibre (<20% ADF and <25% NDF) (see Table 3.7, Chapter 3 and Table 4.9, Chapter 4). Cows feeding on swede and fodder beet are considered potentially susceptible to rumen acidosis because their low fibre feed required less chewing, and thereby less saliva to maintain a normal rumen pH (6.2 – 6.5) (Nichol et al., 2003; Pacheco et al., 2020; Waghorn et al., 2018). The optimum feed ratio of these crops is important in the feed diet to maintain cows' health. For example, it is considered that <40% of fodder beet in daily DMI is recommended for late lactation (Pacheco et al., 2020; Waghorn et al., 2019) but other research highlighted that there was a high risk of acidosis and low milk response if the diet exceeds over 27% daily DMI (Fleming et al., 2020a).

It is important to assess the principal nutritive components of feed for a better understanding of forage nutritive values. However, looking at one attribute alone is not sufficient because other components of feed, diet composition, and presence of pathogens or toxins in plants and animals are also crucial (Waghorn, 2007). The supply of adequate macro- (Ca, Cl, Mg, Na, P, K, and S) and micro-elements (Co, Cu, Fe, I, Mn, Mo, Se, and Zn) is also essential for optimum animal performance (Waghorn & Clark, 2004) and some forages may be deficient in some elements, e.g. forage brassicas (Grace et al., 2000).

6.4 Nitrate leaching losses from maize and winter forage crops

Paddock grazing of forage brassicas is a very common supplementary feeding practice in many areas in NZ (Carey et al., 2017; Westwood, 2021), especially in southern regions of the country (26% in the North Island and 74% in the South Island of the total area of 236,677 ha in 2017) (see Table 2.1, Chapter 2). This practice is associated with high N leaching risks resulting from cow urine patches in the wet season resulting from high N content of forage brassicas (Carey et al., 2017; Malcolm et al., 2016a; Malcolm et al., 2015; Smith & Monaghan, 2020). The higher the N content of forage the higher the N intake in grazing animals and the higher urine N will be (Cichota et al., 2010b; Dijkstra et al., 2013). The typically high N content of brassicas is one of the reasons for high N leaching losses after grazing. Alternative crops with low N content and flexibility in feeding may be able to minimize this problem. Maize silage meets these criteria: low N content and flexibility when feeding being a cut and carry forage. The low N feed of maize not only would be an advantage environmentally but compliments perennial ryegrass-white clover because it nearly always has high N (CP content of up to 30%) (Dalley & Gardner, 2012; Dalley & Geddes, 2012; Waghorn et al., 2007) which could balance the protein inadequacy of maize. Maize can also play an important role in pasture renewal in a rotation where maize is planted for one or two seasons and then returned to pasture.

In the current study, nitrate leaching losses from forage crops were predicted using APSIM after the calculation of cow urine N and N loads per ha based on biomass yield and forage N content using the N excretion equation (Pacheco et al., 2018). Based on 10 kg of daily DMI, per cow urine N (g N/cow/day) was estimated and extrapolated to the total N loads/ha by the multiplication of feed available from 1 ha of production. The key findings of urine N calculation and N leaching losses are summarised below.

6.4.1 Feed nitrogen and urine nitrogen excretion

The individual cow urine N (g N/cow/day) excretion was the lowest when cows were fed maize silage (32.9 g N/cow/day), approximately 75% less (average of grouping all cultivars) compared with that of feeding swede while about 50% less than kale and fodder beet feeding in the 2018/19 season (see Table S 5.1, Chapter 5). Similarly, cows excreted less urine N from the feeding of maize compared with winter forage crops across all MU located trials in the 2019/20 season: 40-67%, ~60%, and 30-42% less urine N per cow per day than swede, kale, and fodder beet, respectively (see Table 5.5, Chapter 5). These figures show that maize could considerably reduce the amount of urine N excretion compared with winter forage crops at the same daily feed intake (10 kg DMI). Other feeding management options such as feeding in off-paddocks, standoff areas, and housing could result in further reduction in excreted N loads to paddocks (Chrystal et al., 2012).

Daily cow urine N excretion was extrapolated to total N loads (kg N/ha) for each crop over the cropping season based on the crop yields obtained from field trials in both years. The total N load per ha from the feeding of maize (82.5 kg N/ha) was not significantly different with kale (108.0 kg N/ha) and fodder beet (122.4 kg N/ha) but 50% less than that of swede (167.4 kg N/ha) in the 2018/19 season (average of grouping all cultivars) (see Table S 5.1, Chapter 5). The total N loads from feeding of maize (115 – 124.5 kg N/ha) were about 24% and 65% higher than forage brassicas (~91.0 kg N/ha) and fodder beet (42.2 kg N/ha), respectively in MU irrigated trial in the 2019/20 season while similar N loads in MU non-irrigated and MU late trials (see Table 5.5, Chapter 5). This is due to the influence of crop yield in the calculation of N loads; maize yields are higher in 2019/20.

Nitrogen will be deposited onto paddocks when grazed occurs. If crops are not fed *in situ* the excreted N load will be zero at the end of the season, but N leaching losses can still happen from the soil-plant-weather interaction during the crop production period. Based on these assumptions, three defined urine N loads (Control = no urine N deposition, Low = lowest urine N loads/ha, and High = highest urine N loads/ha) were simulated in APSIM to estimate nitrate leaching losses from forage crops over 29 years long-term simulations (1991-2020).

6.4.2 Modelling nitrate leaching losses

Simple modelling in APSIM predicted the quantification of nitrate leaching losses from maize and winter forage crops in Manawatu (see section 5.4.5, Chapter 5). The model demonstrated that the maize – ryegrass system can reduce nitrate losses/ha than maize monocrop or winter forage crops in all three N loads deposition scenarios (Control, Low and High) at the end of the cropping season under irrigated and non-irrigated conditions (see Figure 5.4, Chapter 5). However, significant differences in estimated nitrate loss between kale and maize monocrop or maize – ryegrass in the Control and Low N deposition scenarios in both irrigated and non-irrigated conditions occurred. Similarly, the maize monocrop or maize – ryegrass system reduced nitrate losses per ha more than that of both kale and swede crops under the High N deposition scenario in irrigated conditions. However, maize monocrop in non-irrigated conditions was not statistically different from the losses from kale and swede. No significant nitrate losses were observed between maize or maize – ryegrass and fodder beet cropping systems in all urine N deposition scenarios.

Although the modelling demonstrated three different possible scenarios of urine N loads, the Control scenario (no urine N deposition at the end of the crop season) is likely to occur for maize since it is usually fed as silage off-paddocks in NZ farms whereas the High urine N deposition is the most likely scenario for winter forage crops due to the *in situ* grazing of these crops. Therefore, with the consideration of feeding practice, nitrate leaching losses can be summarised as ~21, 126, 162, and 154 kg N/ha under irrigated conditions and 32, 72, 201, and 199 kg N/ha under non-irrigated conditions for maize, fodder beet, kale, and swede, respectively (see Figure 5.4 and Table S 5.5, Chapter 5). This indicates the potential for the maize or maize – ryegrass system to reduce nitrate losses/ha by about 55-85% compared with fodder beet and brassica crops. Nitrate losses from maize in this study are slightly less than the lysimeter and suction cups measurement in Waikato (~60 kg N/ha) but both studies showed the effectiveness of ryegrass on nitrate losses (Tsimba et al., 2020; Tsimba et al., 2022).

6.5 Government or regional councils' regulation on winter grazing

The Government has established and updated resource management regulations (New Zealand Government, 2020), with the implementation of updated intensive winter grazing (IWG) rules from 1 November 2022 (Beef+Lamb New Zealand, 2022; New Zealand Government, 2022). Farmers are allowed to include IWG in their farming systems without resource consent if permitted activities are met. If the IWG activities are beyond the limitations, they will require resource consent. The limitations include restricted activities such as maximum IWG area (not >50 ha or 10% of the farm area), cropping on

10 degree or less slope land, not cropping or grazing in critical source areas, and re-establishment of the vegetation as soon as possible. The details of permitted activities and limitations can be seen on the Government website (https://www.legislation.govt.nz/regulation/public/2022/0119/latest/whole.html).

Regional councils set N leaching loss limits according to their regional plan. However, tools and models used to limit the N loss may differ in each council, for example, the Overseer model in Waikato and Otago Councils, One plan LUC (Land Use Capability) model in the Manawatu region, CNL (Catchment Nutrient Load) and NDA (Nutrient Discharge Allowances) in the Canterbury Council (Hansen & Roberts, 2015).

It is difficult to define N leaching limits for each farming activity, soil classification and region. However, reasonable N loss limits for the dairy regions are summarised here: 12 kg N/ha/yr in the Waikato region (190 kg N/ha fertiliser N cap) (Trebilco, 2020), ~26 – 50 kg N/ha/yr for LUC class 1 to 4 in the Manawatu region (Hanly et al., 2018), 15 kg N/ha/yr in Canterbury (Environment Canterbury, 2018), and 30 kg N/ha/yr in Otago (Hansen & Roberts, 2015).

Our modelling indicates that maize silage would be a useful option in most of these regions. Because maize silage requires a cut and carry feeding system nitrate leaching losses may be confined to <32 kg N/ha compared with the 72 – 201 kg N/ha of nitrate losses from grazing of winter forage crops.

6.6 Implications and opportunities of maize in the future

The yield potential of maize was significantly higher compared with winter forage crops, giving it an edge as the best feed production option available in a pasture-based farming system for the present and the future. Although there is a slight decreasing trend after 2012 (Statistics NZ, 2021), dairy cow numbers are still reaching over 6.1 million in

2021 which is about double compared with cows number in 1992 (see Table 1.1, Chapter 1). Accordingly, supplementary feed use increased from approximately four percent of an average dairy cow diet in 1990-91 to nearly 20% in 2014-15 (Ministry for Primary Industries, 2017). It could be expected that supplementary feed crops will likely play a major role in cow diet in the future. Farmers need to anticipate the future trends to better align their businesses for the requirements of international markets. Farmers should also be aware of their commitment to strategies required to mitigate climate change and environmental impacts. Thus, higher forage yield is a desired factor to maximise the profits as well as to secure the feed supply for the animals over a year.

Maize will potentially be utilized in more areas in the future because of climate change. It is predicted that climate change will cause warming on the east coast and most parts of the North Island while more wet weather in the west (Fitzharris, 2007; NIWA, 2008). With warmer temperatures, there will be more opportunities to grow maize in cooler areas of NZ by achieving the required thermal time as well as through the availability of shorter season maize hybrids. The warmer temperatures may favour maize production in a range of areas in the South Island. For example, it is likely to expand the southern limits (mid-south Canterbury) of maize growing (Wilson et al., 1994) with the availability of shorter season hybrids and frost-resistance hybrids in the future (Densley et al., 2004).

Similarly, maize could be grown at higher altitude North Island sites (e.g. Kiwitea) currently considered too cold to grow maize reliably. Despite the higher altitude, maize performance from the Kiwitea trial proved competitive with other forage crops with a shorter crop duration.

Before the year 2000, maize was assumed a risky crop for the South Island because of frost damage risk or insufficient heat units to reach harvest maturity particularly if sown late (Wilson et al., 1994). For example, there were only 153 ha of maize harvested area in the South Island in the 1981-82 season (Anon cited in Bansal & Eagles, 1985). This perspective has changed due to the warmer climate and technological developments (e.g. photo-degradable plastic mulch, shorter maize hybrids, etc.). At present, maize silage is being grown in southern parts of the country, albeit at low levels, reaching 537 ha (harvested area) in Otago and Southland out of total 4094 ha in the South Island (Statistics NZ, 2017). The total harvested maize silage area in 2021 is 55,241 ha (Arable Industry Marketing Initiative, 2021), and there is potential to expand the sown areas with the available technology and favourable climate under the increasing feed demand of dairy expansion in the South Island.

Soil temperature (<9°C) is the most limiting environmental factor for crop growth in early spring and winter in the South Island (Dalley & Van der Poel, 2008). The use of photo-degradable plastic mulch has the potential to overcome this limitation because it improves soil temperature (~5°C) at 5 cm depth, so enhances crop establishment, a faster canopy and reproductive development in maize crops. Plastic mulching does not appear to increase final yield (Fletcher et al., 2008a; Fletcher et al., 2008b). This technology would be useful for cooler areas of NZ to help ensure good establishment of maize crops and bring harvest forward about two weeks, reducing the risk of late-season frost damage.

6.7 General conclusion

Maize yields were on average 50-60% greater than winter forage crops under high N fertilisation, irrigation regimes, and late sowing conditions at Massey University located trials in 2018/19 and 2019/20. At Tokoroa and Kiwitea, maize produced similar yields to winter forage crops. Although the opportunity of cover crop planting after maize harvest depends on weather conditions or moisture availability, it was evident that maize

– ryegrass double-cropping significantly outyielded the winter forage crop options over the same crop duration of eight or nine months (from November to June/July). In addition, the cover crop could reduce 20-30% in total nitrate leaching losses in the modelling study.

Forage quality analysis in 2018/19 (Chapter 3) and 2019/20 (Chapter 4) seasons showed that the energy (ME) profile of forage crops was good (~11 MJ ME/kg DM). Maize and fodder beet both had CP contents <10% while the forage brassicas (kale and swede) achieved CP around 14-15%. Swede and fodder beet generally has low fibre content, below the recommended levels for the dairy cows (>21% ADF and >33% NDF). Low fibre with high sugar feed results in less chewing, so it could cause animal health issues such as rumen acidosis.

Modelling revealed that low CP forage, produced lower urine N excretion per animal and per ha. Estimated urine N excretion per cow was 40-60% lower for maize compared with the winter grazed forage crops. However, total N loads/ha was not different between maize and winter forage crops due to the influence of crop yields in the calculation. This means that total N loads/ha become balanced when lower per-cow urine N excreted maize has higher yield/ha (or) when higher per-cow urine N excreted winter forage crops have lower yield/ha in the calculation.

The modelling study confirmed that the higher N loading at the end of the cropping season causes potentially higher nitrate leaching losses. In addition, *in situ* grazing crops (swede, kale, and fodder beet) were more vulnerable to nitrate leaching losses compared with the harvested crop (maize) if the common feeding practice is considered. Therefore, it can be concluded that predicted nitrate leaching losses for fodder beet, kale, and swede crops were 126, 162, 154 kg N/ha under irrigated conditions and 72, 201, 199 kg N/ha under non-irrigated conditions, respectively in grazing systems (High N deposition *in situ* grazing). In contrast, nitrate losses for maize or maize –

ryegrass were 21 kg N/ha under irrigated conditions and 32 kg N/ha under non-irrigated conditions in off-paddocks feeding systems (No urine N deposition on paddocks).

Field experiments and APSIM simulation confirmed that maize is a viable alternative option to winter forage crops in terms of yield and feed quality as well as higher potential in minimising nitrate leaching risks if typical feeding practice is considered.

6.8 Constraints experienced during the study

6.8.1 Weed control

Weed control was inadequate at the Tokoroa site in the 2018/19 season, requiring two or three hand weeding events to achieve weed-free conditions. Weed infestation was problematic during the early establishment of crops, resulting in a complete loss of fodder beet. Weed control was also a major task in multi-environment trials in the second season (2019/20).

6.8.2 Travel restriction

COVID-19 travel restriction and nationwide lockdown (March-May 2020) prohibited access to the trial sites and sample processing operations at Massey University laboratory in the second season (2019/20). As a result, there were 2-3 weeks of delay in the harvesting of maize silage at Massey University late and Kiwitea late trials in the 2019/20 season. In addition, maize plant component ratios were not collected from the Massey University irrigated and non-irrigated trials in the 2019/20 season because these trials were harvested without delay on the 24 March 2020 to meet the acceptable harvest silage dry matter content of 30-38% as well as to beat the lockdown call after the government announced a nationwide lockdown on the 23 March 2020.

6.8.3 Bird damage

At Massey University late trial (2019/20), maize seedlings in 2-3 replicates were impacted by birds after emergence (~10 DAS). However, the losses were recovered, and gaps filled with the same hybrids from the neighbouring plots in the trials. Again, maize grains were eaten by birds in some plots just before harvesting at MU late trial. The impact was assessed, and the yield losses calculated accordingly (Chapter 4).

6.8.4 Data availability in modelling

The APSIM model needs detailed soil data inputs to simulate the soil water movements and nitrogen dynamics. If possible, the field measurement of soil data is recommended. However, this is not always feasible. In such a case, similar soil data from the nearest site can be used to demonstrate the model outputs in the simulation. It was feasible to use previous soil data at Massey University located trials, but detailed soil information was not available for the Kiwitea site.

6.8.5 Lack of full crop models for swede and kale

APSIM model includes several crop models developed by a group of modelers, agronomists, and researchers around the world using plant modelling framework (PMF), but full crop models are still limited for some crops. In this modelling study, the APSIM-SCRUM model was not the full crop model specific to kale and swede crops compared with APSIM-Maize and APSIM-Fodder beet. However, the SCRUM model was designed for several forage crops used in NZ farming systems to estimate water and nitrogen balances. Therefore, care should be taken in interpreting the results of predicted biomass yield since yield could be reduced if N or water supplies are insufficient (https://builds.apsim.info/api/nextgen/docs/SCRUM.pdf). However, nitrate leaching losses estimations from kale and swede are in a reasonable range compared to the previous literature in NZ.

6.9 Recommendations for future research

1. Side-by-side field measurements of nitrate leaching losses for maize silage and winter forage crops using a ceramic cup sampler or lysimeter study would be useful to validate the APSIM modelling outputs. Although numbers of field measurements on nitrate leaching losses were taken on a single crop, no side-by-side comparison of maize and winter forage crops was conducted to our knowledge. It could be useful to compare the leaching results from a specific soil under the same climate and weather conditions over a range of locations.
2. Long-term rotational research on maize and winter forage crops (3-5 years) would be useful for farmers to assess how maize silage could be fit or be integrated with a typical pasture system.
3. Along with the long-term rotational study in step 2, the cost and benefit assessment of maize-ryegrass vs winter forage crops would be useful for the farmers in making the cropping choice. Future research should focus on the economic viability of these forage crops with a detailed cost and benefit analysis from cropping to the production of milk over a 2–3-year period.
4. With the warming climate, maize silage will be better adapted to the cooler areas of NZ in the future, but the trials testing maize performance in cooler NZ areas are very limited. It could be useful to assess the adaptability of maize silage on-farm trials in southern locations or higher altitude sites of the country under a range of agronomic practices, such as growing under plastic mulch, using

different hybrids maturity classes, field germination tests for cold and frost resistance.

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Appendices

Appendix A. Soil properties of experimental sites prior planting in the 2018-2019 and 2019-2020 seasons.

Fertility indicator	Units	2018-2019		2019-2020		Medium range
		Massey University	Tokoroa	Massey University[a]	Kiwitea	
Sampling date		11 Oct 2018	29 Oct 2018	1 Nov 2019	29 Nov 2019	
pH		5.6	5.6	5.3	5.7	5.8 – 6.2
Volume weight (laboratory bulk density)	g/mL	0.97	0.62	1.02	0.98	0.6 – 1.0
Olsen P	mg/L	30	34	60	24	20 – 30
QT K[b]		5	4	7	8	-
QT Ca[b]		9	4	7	7	-
QT Mg[b]		23	13	24	18	-
QT Na[b]		6	4	3	5	-
Exchangeable K	me/100 g	0.26	0.35	0.33	0.4	0.3 – 0.6
Exchangeable Ca	me/100 g	7.3	5.4	5.3	5.4	5 – 12
Exchangeable Mg	me/100 g	1.03	0.94	1.05	0.84	0.6 – 1.2
Exchangeable Na	me/100 g	0.13	0.15	0.07	0.11	0.2 – 0.5
CEC	me/100g	14	19	13	13	12 – 25
Total N	%	0.24	0.55	0.21	0.3	0.3 – 0.6
Total C	%	2.3	6.8	2.1	3.3	-
Organic matter	%	3.9	11.8	3.7	5.7	7 – 17
Available N	kg N/ha	93	77	99	160	100 – 150
Ammonium N	mg/kg	6	13	4	20	-
Nitrate N	mg/kg	15	2	11	20	-
Mineral N (Nitrate-N + Ammonium-N)	mg/kg	21	15	15	40	-

Note: Sampling depth was 0-15 cm, unless specified. [a] Soil sampling is done for all three trials at Massey University in the 2019-2020 season since the trials are adjacent to each other on the same paddock. [b]MAF quick test (QT) units.

Appendix B. Monthly rainfall (mm), mean daily maximum, minimum and average temperatures (°C), soil temperature at 10 cm (°C), daily sunshine (hours), and daily wind run (km) recorded at AgResearch, Palmerston North from November 2018 to October 2019.

Month	Rainfall (mm)	Temperature (°C)			Soil temp (°C)	Sunshine (hrs)	Wind run (km)
		Max	Min	Mean			
November	90.8	20.0	10.2	15.1	15.5	156.8	324.2
December	173.0	22.9	12.9	17.9	18.3	158.8	311.8
January	30.8	23.7	15.1	19.4	20.2	210.4	393.7
February	30.0	23.7	12.0	17.9	18.9	211.0	284.3
March	51.6	23.9	12.7	18.3	17.3	214.2	274.4
April	81.0	18.7	8.3	13.5	12.8	135.2	227.8
May	59.5	17.4	7.5	12.4	10.9	95.6	241.3
June	124.6	13.9	3.8	8.8	7.5	111.3	214.1
July	98.6	14.6	5.6	10.1	7.9	100.6	214.9
August	117.0	13.4	4.4	8.9	7.7	116.3	298.7
September	60.6	15.0	6.4	10.7	9.7	106.4	355.2
October	97.6	16.3	7.5	11.9	11.4	122.8	345.8
Average	**84.6**	**18.6**	**8.9**	**13.7**	**13.2**	**145.0**	**290.5**

Appendix C. Monthly rainfall (mm), mean daily maximum, minimum and average temperatures (°C), soil temperature at 10 cm (°C), daily sunshine (hours), and daily wind run (km) recorded at AgResearch, Palmerston North from November 2019 to October 2020.

Month	Rainfall (mm)	Temperature (°C)			Soil temp (°C)	Sunshine (hrs)	Wind run (km)
		Max	Min	Mean			
November	78.8	20.5	9.9	15.2	15.4	219.1	321.7
December	124.2	21.3	12.1	16.7	17.3	192.3	345.5
January	31.6	22.4	12.9	17.7	18.3	184.9	350.0
February	35.4	25.0	13.8	19.4	19.5	222.2	326.4
March	48.8	21.5	11.1	16.3	15.9	172.4	285.2
April	65.6	19.0	8.4	13.7	12.9	181.6	259.4
May	66.2	16.7	7.1	11.9	10.2	149.2	230.3
June	64.6	14.9	8.0	11.4	9.9	88.6	287.1
July	65.0	13.4	4.7	9.0	7.5	119.6	263.3
August	40.0	14.7	5.3	10.0	8.4	121.4	251.9
September	137.6	15.0	6.8	10.9	10.3	140.0	368.6
October	63.0	18.0	8.9	13.4	13.3	147.9	305.1
Average	**68.4**	**18.5**	**9.1**	**13.8**	**13.2**	**161.6**	**299.5**

Appendix D. Monthly rainfall (mm), mean daily maximum, minimum and average temperatures (°C), soil temperature at 10 cm (°C) recorded at Tokoroa from November 2018 to October 2019. Rainfall data was downloaded from Lichfield Station [Agent number = 12558]. Temperature was downloaded from Mamaku Radar Wxt Aws Station [Agent number = 38671] NIWA Cliflo.

Month	Rainfall (mm)	Temperature (°C)		
		Max	Min	Mean
November	122.1	15.3	8.8	12.1
December	225.7	18.3	11.7	15.0
January	-	21.2	13.1	17.2
February	28.8	20.9	12.5	16.7
March	44.8	19.6	13.0	16.4
April	75.4	14.9	9.0	12.0
May	96.2	13.1	8.5	10.8
June	80.1	10.0	5.2	7.6
July	160.4	10.2	6.4	8.3
August	203.2	9.2	4.6	6.9
September	123.3	11.2	5.9	8.5
October	96.6	12.6	7.0	9.7
Average	**114.2**	**14.7**	**8.8**	**11.8**

Note: other climatic data are not available at Tokoroa.

Appendix E. Monthly rainfall (mm), mean daily maximum, minimum and average temperatures (°C), soil temperature at 10 cm (°C) and daily wind run (km) recorded at Kiwitea from November 2019 to October 2020. Rainfall data was download from Waituna Station [Agent number = 3174] (11 km distance from the trial site). The remaining data were downloaded from Palmerston North Aws Station [Agent number = 3243] NIWA Cliflo. The downloaded temperature range here might be different from on-site recorded temperature using MicroLoggers (Chapter 4) due to 27 km distance.

Month	Rainfall (mm)	Temperature (°C)			Wind run (km)
		Max	Min	Mean	
November	57.2	20.6	9.9	15.3	371.8
December	83.2	21.7	12.1	16.9	412.7
January	23.8	23.2	12.9	18.0	439.3
February	14.5	25.9	13.5	19.7	392.2
March	41.9	22.3	11.0	16.7	365.1
April	50.7	19.5	8.9	14.2	342.1
May	93.2	16.7	6.5	11.6	307.4
June	70.3	15.0	7.8	11.4	372.5
July	65.3	13.4	5.3	9.3	365.1
August	47.1	14.6	5.5	10.0	330.4
September	135.3	14.8	7.1	11.0	-
October	83.4	17.9	9.4	13.7	368.7
Average	**63.8**	**18.8**	**9.2**	**14.0**	**369.8**

Note: Other climatic data are not available at Kiwitea.

Appendix F. Chlorophyll concentration measurement using SPAD meter readings at Palmerston North, New Zealand during the 2018 – 2019 season.

Leaf chlorophyll concentration was monitored non-destructively by using CCM-200 plus chlorophyll content meter to assess N response of the cultivars and to ensure the N supply meets crop demand at Palmerston North in 2018/19. However, the data was not reported in the thesis.

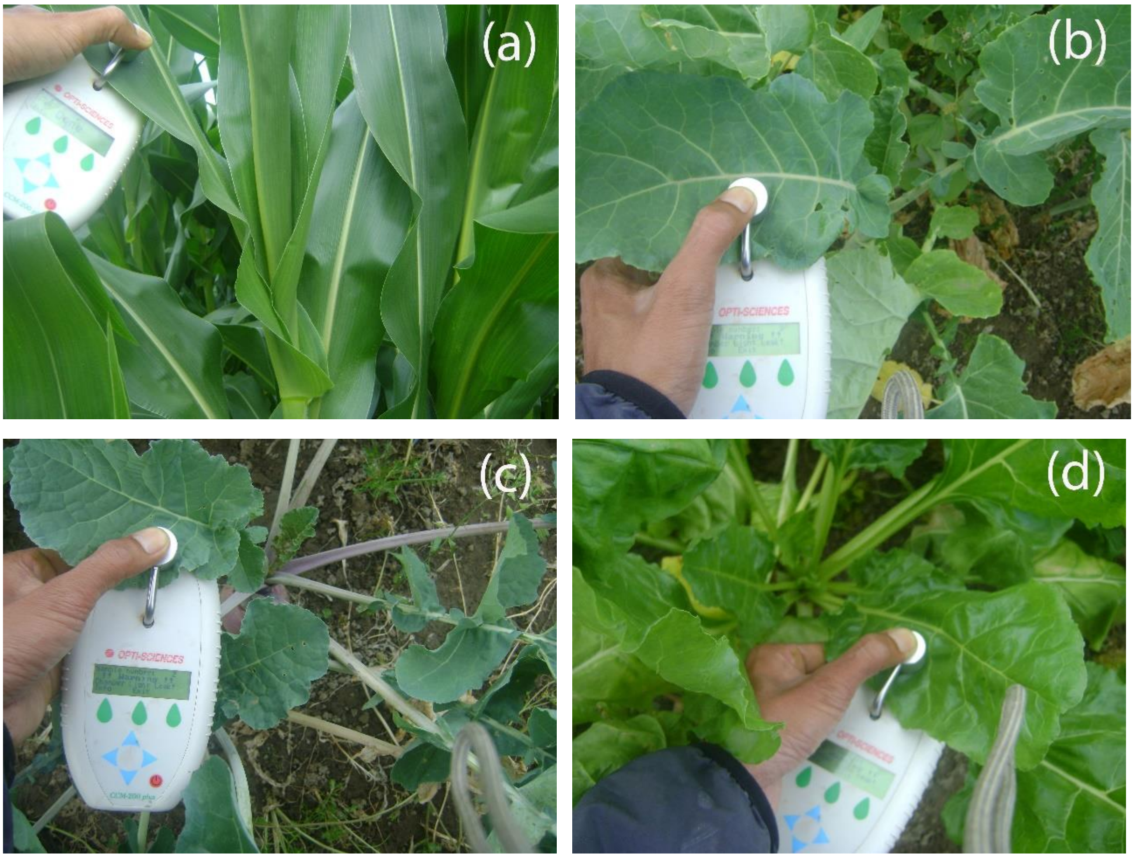


Plate. Leaf chlorophyll measurements with CCM-200 plus chlorophyll meter on (a) maize, (b) kale, (c) swede and (d) fodder beet crops.

The chlorophyll concentration index (CCI) reading was measured from 30 DAS to 120 DAS (until maize harvest). The CCI values varied in all forage crops, with a particular difference between with and without N application. Within each group of crops, the CCI values of the forage crops showed an obvious increase in all crops after N fertiliser was applied on 21st December 2018 (200 kg N/ha, 38 DAS) and 24th January 2019 (100 kg N/ha, 72 DAS). N fertiliser application also coincided with the crop demand N. This was noted as the crops showed particularly low chlorophyll concentrations before N application times.

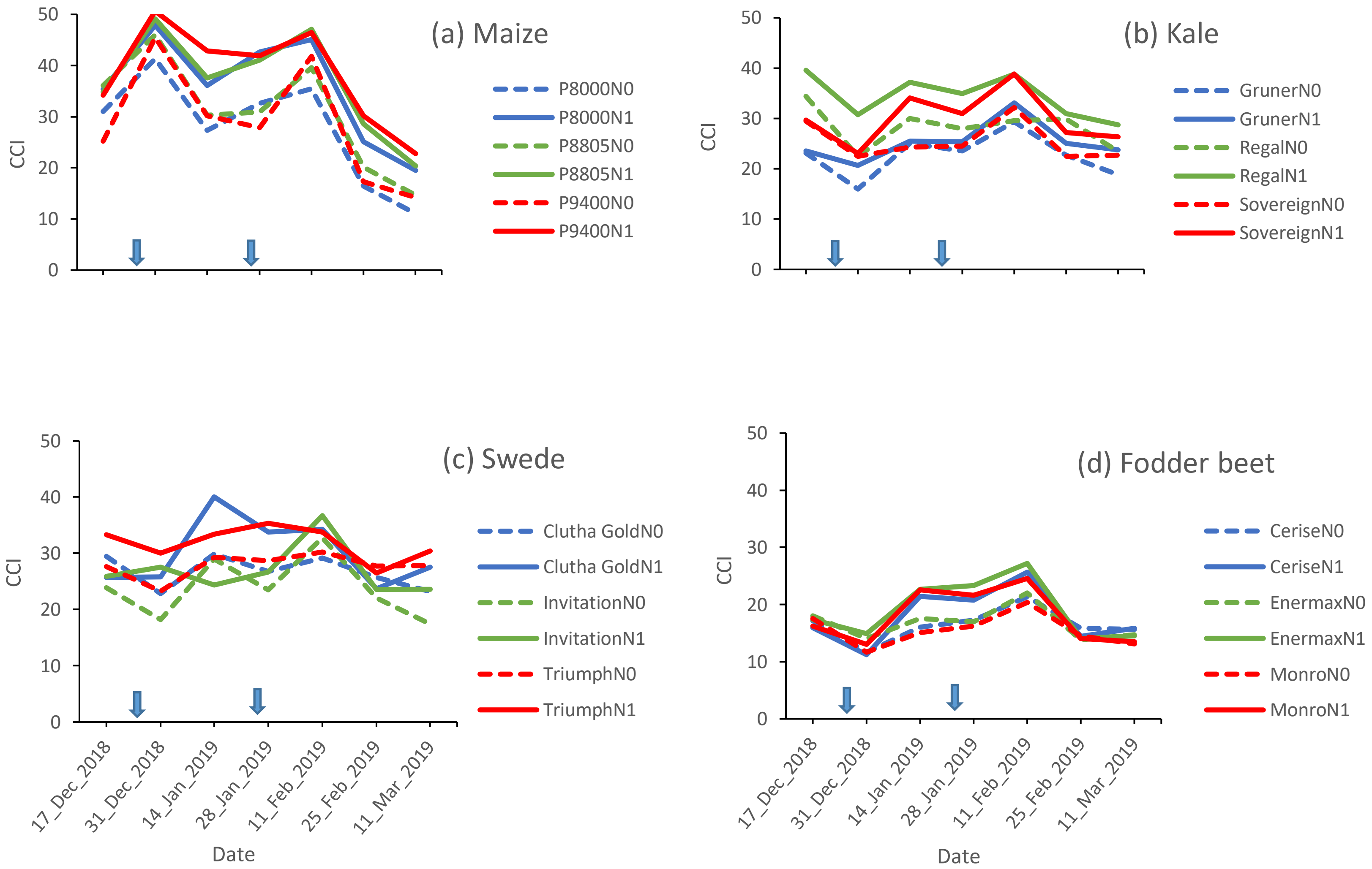


Figure. Chlorophyll concentration index (CCI) values of forage cultivars as affected by N application (down arrows show the time of N fertiliser application). N0 = Control (0 kg N/ha), N1 = High-N (300 kg N/ha).

Appendix G. Locational effects on plant components of maize at Massey University and Kiwitea in 2019/20.

Site	Grain (%)	Cob (%)	Leaf (%)	Stem (%)	Silage DM (%)
	Maize P8000				
MU late	54.2	16.7	9.7	19.4	56.1
Kiwitea late	46.0	15.1	16.2	22.7	44.2
LSD (*P* = 0.05)	NS	NS	3.6	NS	6.8
P > F	0.0653	0.3761	0.0103	0.2260	0.0113
	Maize P8805				
MU late	52.6	15.4	11.5	20.5	54.1
Kiwitea late	50.3	13.4	16.6	19.7	44.0
LSD (*P* = 0.05)	NS	NS	2.5	NS	8.2
P > F	0.2319	0.3265	0.0074	0.3769	0.0294

NS, not significant.

Note: data was not collected from MU irrigated and non-irrigated trials due to the COVID-19 lockdown on 25 March 2020.

Appendix H. Locational effects on plant components of kale, swede, and fodder beet at Massey University and Kiwitea in 2019/20.

Site	Kale		Swede		Fodder beet	
	Leaf (%)	Stem (%)	Leaf (%)	Bulb (%)	Leaf (%)	Bulb (%)
MU irrigated	24.8	75.2	11.6	88.4	12.5	87.5
MU non-irrigated	42.2	57.8	9.4	90.6	22.6	77.4
MU late	37.8	62.2	10.9	89.1	19.3	80.7
Kiwitea late	40.4	59.6	26.2	73.8	18.5	81.5
LSD (P = 0.05)	9.0	9.0	5.0	5.0	5.5	5.5
P > F	0.0072	0.0072	0.0001	0.0001	0.0165	0.0165

NS, not significant.

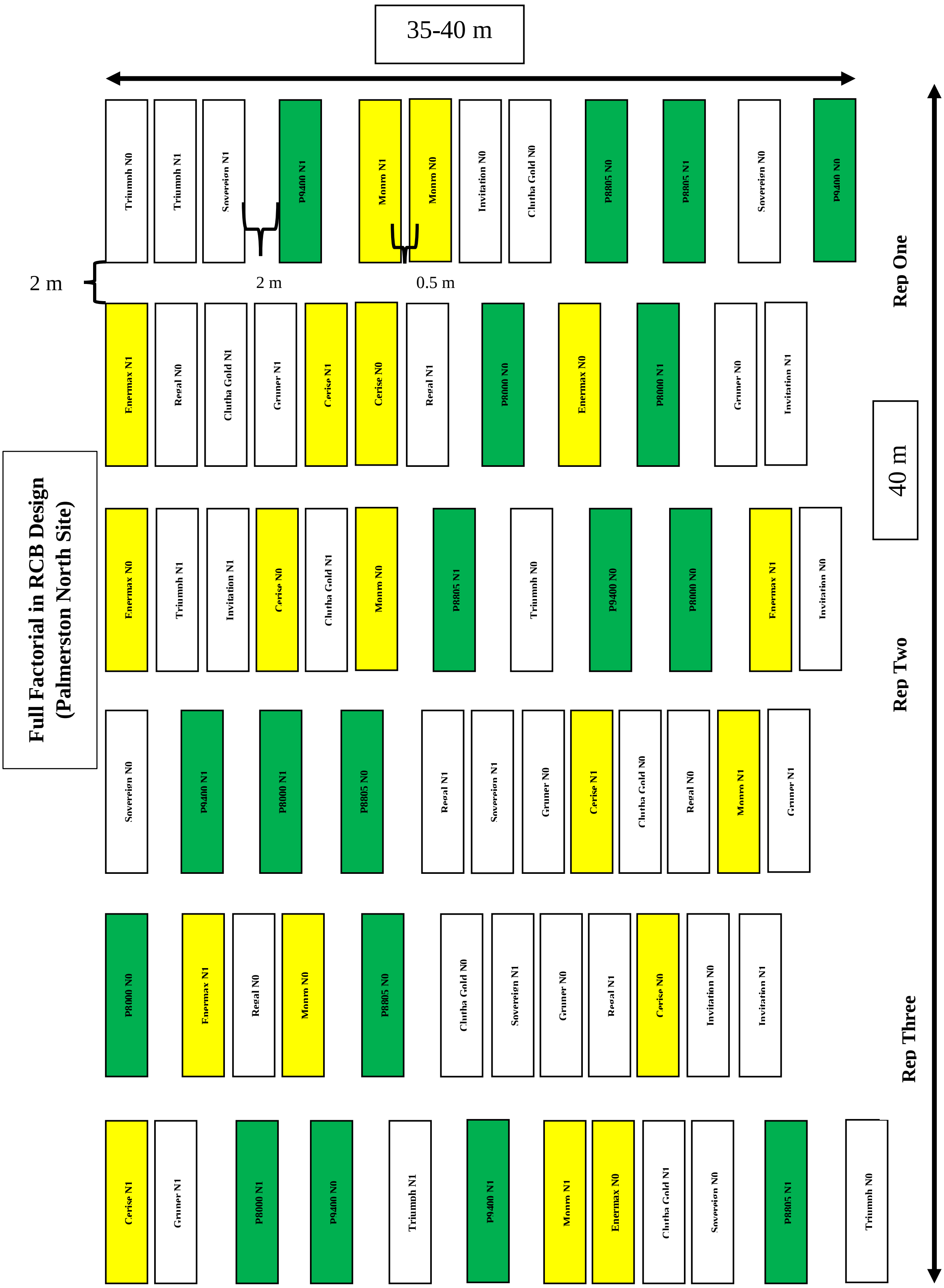
Appendix I. Post-grazing residual score of forage crops at Massey University, New Zealand in the 2019/20 season.

Treatments	Massey site		
	Irrigation	Non-irrigation	Late-sowing
P8000-Ryegrass	-	-	-
P8805-Ryegrass	0.3	2.0	-
P9400-Ryegrass	0.8	2.3	-
Kale	4.5	4.0	4.8
Swede	5.5	3.8	4.9
Fodder beet	2.5	2.0	5.1
LSD $_{(0.05)}$	1.4	0.8	1.8
Treatments	***	***	NS

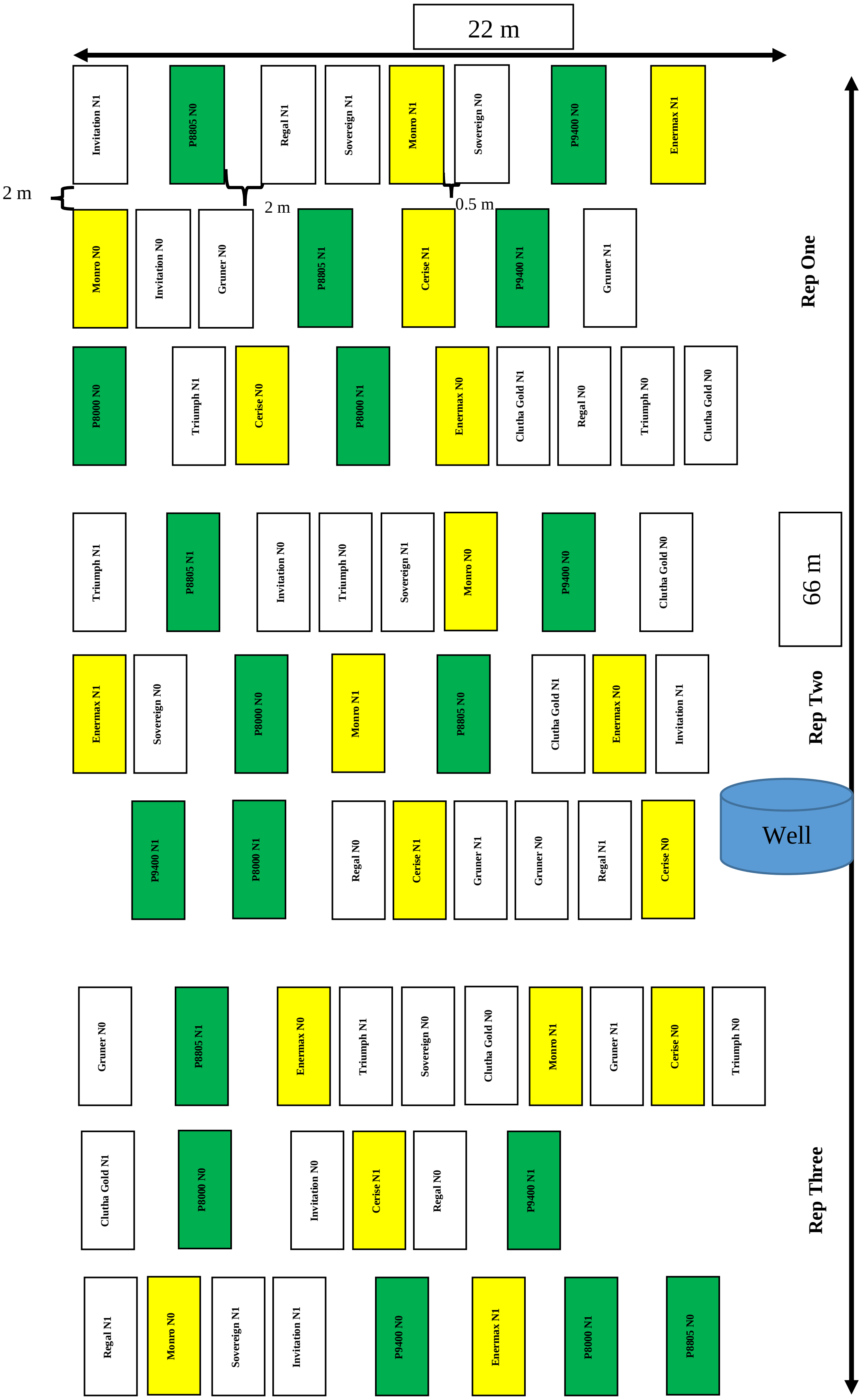
***P<0.001, NS, not significant
(1=completely grazed, 10 = ungrazed plot)

Post-grazing residual score assessment has followed the procedure by Millner (1993). Residual scores were based on visual estimation of the % utilization on each plot; 1 = completely grazed, 10 = ungrazed plots. Due to the management reason, sheep grazed all plots in the whole experimental area (20 x 40 m^2) with access to all crops in the trial after two weeks of harvest. Grazing intensity is 670 one-year-old hogget/ha/day for two days in each trial, which is similar to ~500 mixed ewes/ha for three days in Millner (1993). At the grazing time, irrigated and non-irrigated trials had ryegrass on maize plots, so the analysis included ryegrass in those trials but not on the MU late sown trial.

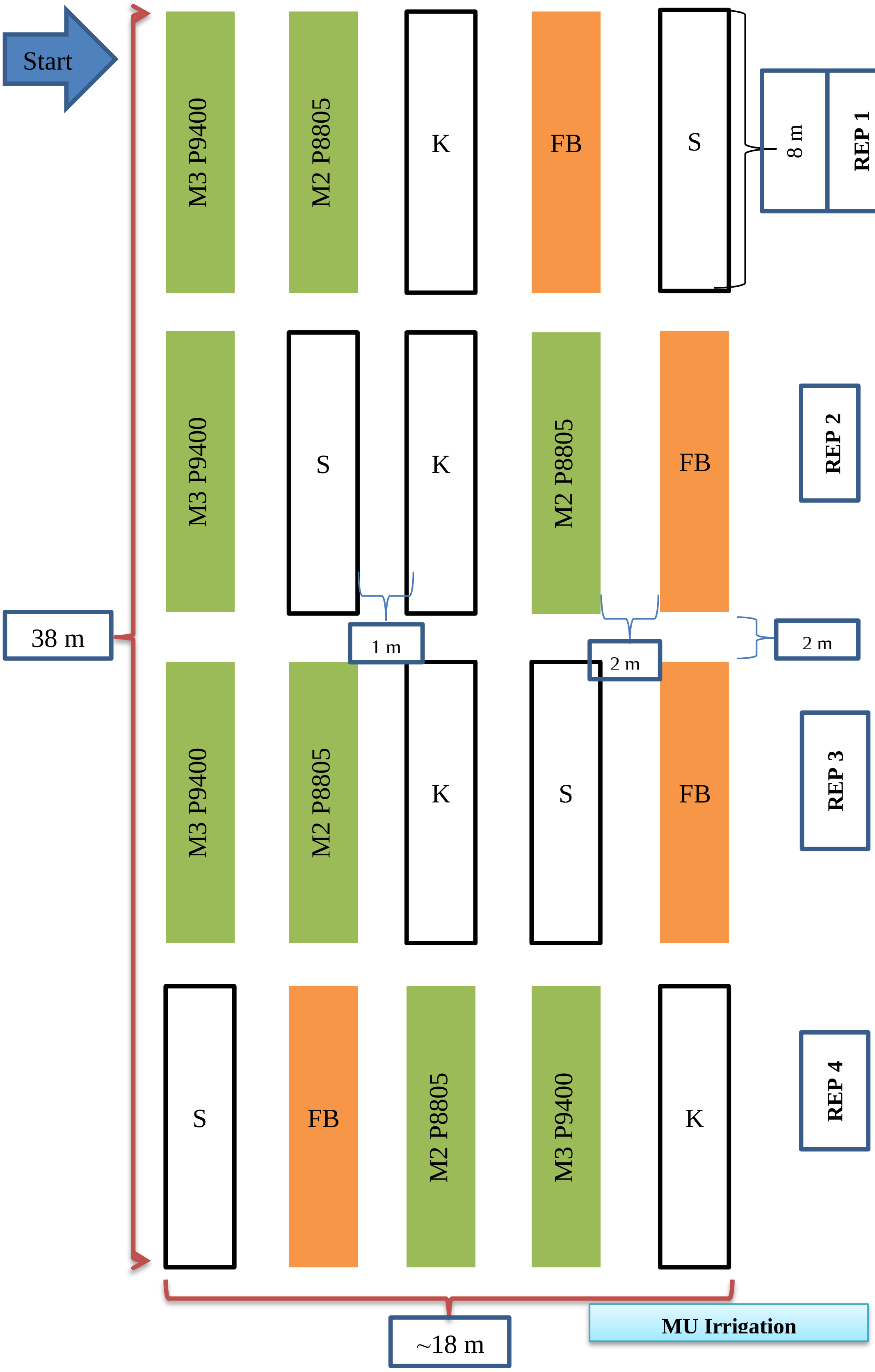
Appendix J. Plot layouts for factorial arrangement in randomized complete block design at Massey University and Tokoroa in 2018 – 2019. Twelve forage entries and N fertiliser application: N0 = Control (0 kg N/ha) and N1 = High-N (300 kg N/ha).

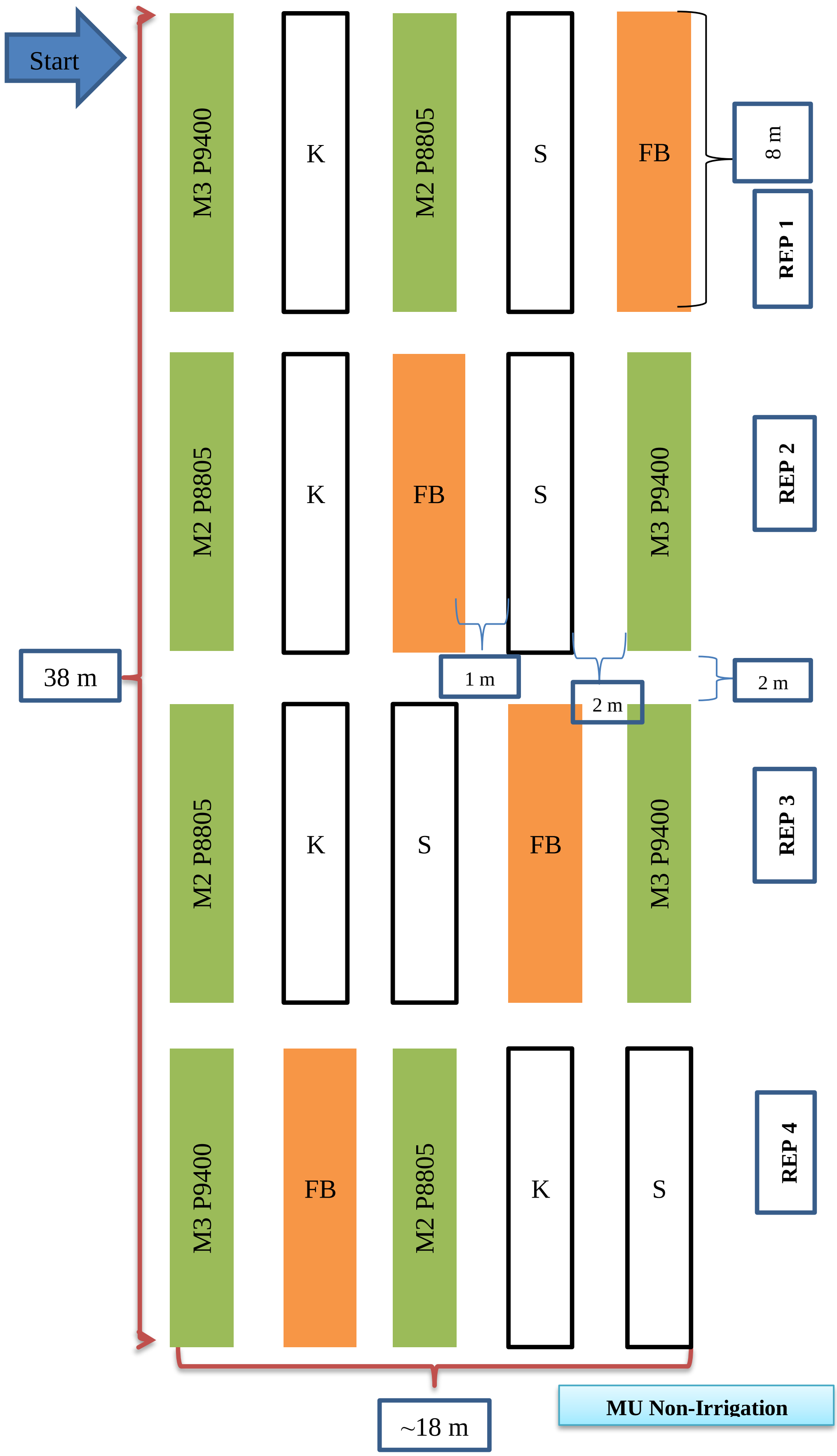


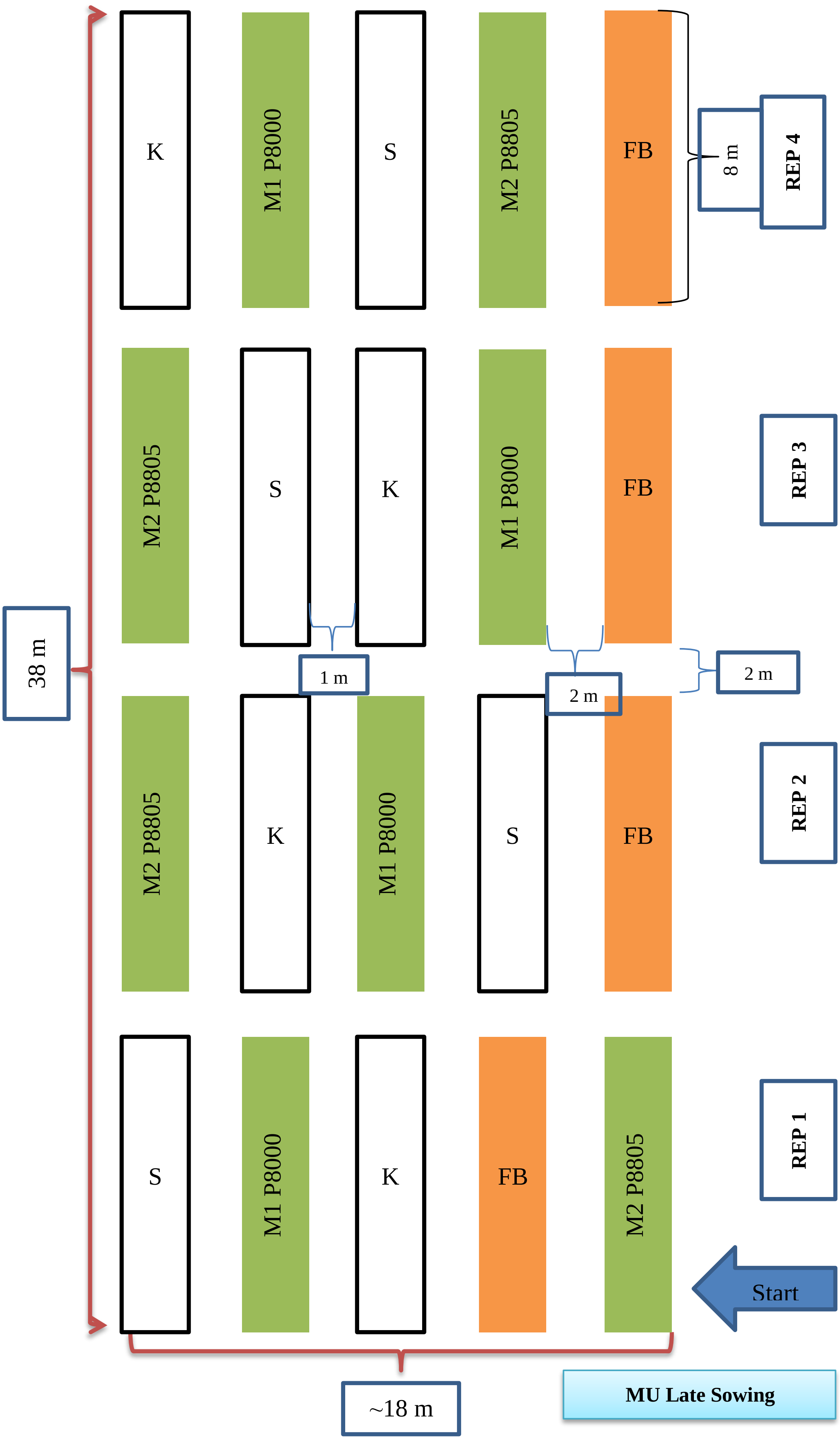
Full Factorial in RCB design
(Tokoroa site)

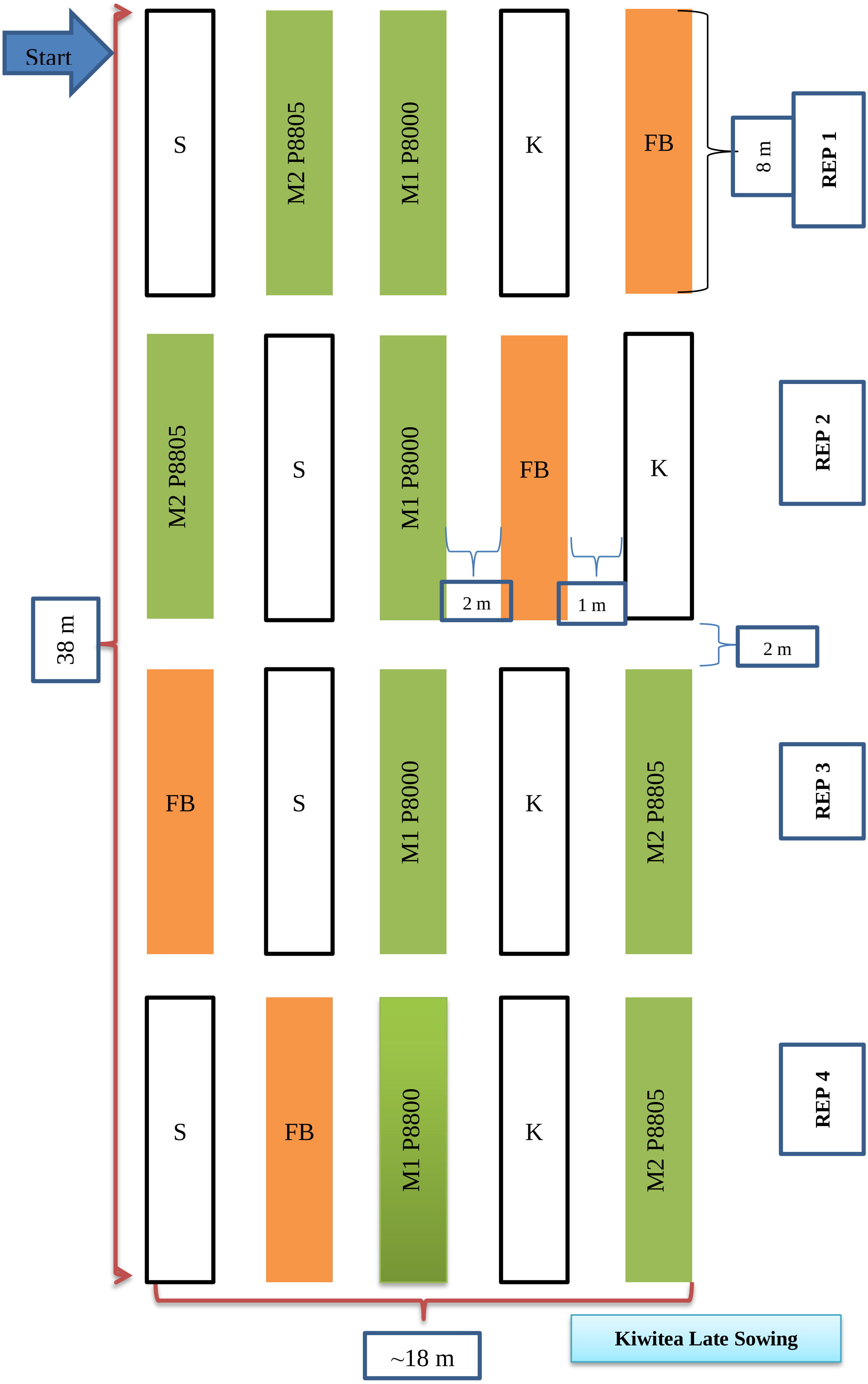


Appendix K. Plot layouts for randomized complete block design at Massey University (MU Irrigation, Non-irrigation, Late sowing trials) and Kiwitea (Late sowing trial) in 2019 – 2020. K = Kale, S = Swede, and FB = Fodder beet, M = Maize silage.




Start
M3 P9400
K
M2 P8805
S
FB
8 m
REP 1
M2 P8805
K
FB
S
M3 P9400
REP 2
1 m
2 m
2 m
38 m
M2 P8805
K
S
FB
M3 P9400
REP 3
M3 P9400
FB
M2 P8805
K
S
REP 4
~18 m
MU Non-Irrigation


K
M1 P8000
S
M2 P8805
FB
8 m
REP 4
M2 P8805
S
K
M1 P8000
FB
REP 3
38 m
1 m
2 m
2 m
M2 P8805
K
M1 P8000
S
FB
REP 2
S
M1 P8000
K
FB
M2 P8805
REP 1
Start
~18 m
MU Late Sowing


Start
S
M2 P8805
M1 P8000
K
FB
8 m
REP 1
M2 P8805
S
M1 P8000
FB
K
REP 2
2 m
1 m
38 m
2 m
FB
S
M1 P8000
K
M2 P8805
REP 3
S
FB
M1 P8800
K
M2 P8805
REP 4
~18 m
Kiwitea Late Sowing

Appendix L. Disease diagnostics of kale plants from the first season trial at Massey University, New Zealand in 2018/19.

PLANT DIAGNOSTICS

PLANT DIAGNOSTICS Limited
185 Kirk Road
PO Box 23-122
Hornby
Christchurch 8441

Phone: 03 3779026
Email: enquiries@plantdiagnosticslimited.co.nz
Web: www.plantdiagnosticslimited.co.nz

3 September 2019

Aung Myo Thant
Massey University
AHB 3.12
Riddet Road
Palmerston North

Email: A.Thant@massey.ac.nz

Re: Sample of Sovereign and Regal Kale (Laboratory Reference A3392)

Description
Black stem lesions

Identification by morphology
Symptomatic plant tissues were plated to agar media to test for plant pathogens.

Pathogens detected were:

- *Xanthomonas campestris* (black rot) main disease
- *Phoma* species (closest alignment to *Phoma herbarum*, a saprophyte)
- *Fusarium lateritium* (likely secondary pathogen)
- *Alternaria alternata* (saprophytic or secondary pathogen)

Symptoms observed on your sample

Stem lesions

***Xanthomonas* growing on agar**

Interpretation
The cause of these symptoms was black rot (*Xanthomonas campestris pv campestris*) which is a serious disease of many brassica species and can potentially lead to complete crop failure. This disease may be introduced on seed or if planted in the field may have survived on infected plant material from previous crops. The bacterium spreads in water

droplets and therefore the movement of people or equipment through the crop or plants when leaves are wet from rain, irrigation or dew is best avoided. Spread is especially important when plants are young. Warm wet or humid conditions favour disease development and spread. There is no practical control at this stage. Prevention of infection by use of clean seed and the strictest hygiene during early production is crucial in avoiding disease epidemics. A low rate of seed infection could potentially result in a serious infection in the crop due to the ability of the bacteria to spread during the early seedling stage and then during crop maintenance (passing of machinery and people through the crop especially if there is leaf wetness). It is best to use soils which have not grown brassica crops for at least 3-4 years. Deep ploughing will help reduce disease inoculum. Controlling brassica weeds which may act as a source of infection and controlling weeds in general to reduce humidity should help provide conditions less conducive to disease development.

The other pathogens detected are likely secondary to the black rot and not the primary cause of the observed symptoms.

If you have any further questions regarding these findings then please don't hesitate to contact us.

Yours sincerely

M. Braithwaite

Mark Braithwaite (Plant Pathologist)

Appendix M. Statement of contribution to Doctoral thesis containing publications (form DRC 16).

DRC 16

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

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

Name of candidate:	Aung Myo Thant
Name/title of Primary Supervisor:	Dr James Millner
In which chapter is the manuscript /published work: Chapter 3	

Please select one of the following three options:

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

- Please provide the full reference of the Research Output:

Thant, A. M., Millner, J. P., McGill, C. R., & Tsimba, R. (2020). Productivity and quality of kale, swede, fodder beet and maize in Manawatu. Agronomy New Zealand, 50, 81-93.

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

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

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

Candidate's Signature:	
Date:	08-Jul-2022
Primary Supervisor's Signature:	James Millner Digitally signed by James Millner Date: 2022.07.08 10:11:49 +12'00'
Date:	8-Jul-2022

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

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

Appendix N. Note for examiners – explanation of COVID-19 impacts.

Please consider the factors listed below in your assessment of the work.

This statement has been prepared by the candidate's supervisor in consultation with the student and has been endorsed by the relevant Head of Academic Unit.

Student Name:	Aung Myo Thant	ID Number:	18035578
Supervisor Name:	Dr James P. Millner	Date:	29-Jul-22
Thesis title:	Comparison of maize silage and traditional forage crops in New Zealand		

Considerations to be taken into account. Note: This statement will remain in the final copy of the thesis which will be available from the Massey University Library following the examination process.
[Enter key considerations here for the examiners. This can include but is not limited to change of scope, scale, topic, focus; limitations in relation to data collection, access to necessary literature or archival materials, laboratories, field sites; disruptions as a result of lockdown and various alert levels, medical or health considerations etc]

Covid 19 affected Aung's ability to conduct his field trials on a number of occasions. For example, during the 1st lockdown in March/April 2020 we were unable to access the campus at all and could not harvest the maize plots at the Kiwitea site or the Massey late trial. Both trials were eventually harvested when the lockdown conditions eased slightly, though Aung was not able to be travel to the Kiwitea site due to the need to maintain household bubbles. His supervisor harvested that trial. The late harvests resulted in issues including bird damage, especially at the Massey site.

Other issues included delays in processing samples submitted for analysis of forage quality which delayed statistical analsis and writing of the thesis. An extension of the thesis submission date based on these issues was sought and granted.

Approved by DRC 10/Feb/2021
DRC 21/02/03

Confidential for Examiners Only: *[Please enter any other considerations which are confidential for examiners only and should not be placed in the final thesis version submitted to Library following the examination process]*

Signed, confirming this is a fair reflection of the impact of Covid-19 on this research.

Student	Aung Myo Thant	Aung Myo Thant 2022.07.13 14:26:05 +12'00'
Supervisor	James Millner	Digitally signed by James Millner Date: [illegible]
Head of Academic Unit (or nominee)		

Approved by DRC 10/Feb/2021
DRC 21/02/03