Impact of regenerative agriculture on radiation use efficiency of grassland production

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Regenerative agriculture has received more and more attention within recent years and has been promoted as a method to mitigate climate change by increasing soil carbon storage. Furthermore it is described as a way to increase biodiversity, provide a solution for declining health of freshwater ecosystems and water quality, and improve the wellbeing of farmers and communities. The aim of this dissertation was to investigate the effectiveness of regenerative agriculture for improving the radiation (light) use efficiency of grassland production. A dataset of grassland radiation-use efficiency and explanatory variables was collected from 4.5 months (15 February to 28 June 2023) of a new farmlet-scale experiment, the "Regenerative Agriculture Dryland Experiment" (RADE) at Lincoln University, New Zealand. The experiment compared two systems of grassland-based sheep production, a regenerative agriculture system comprising species-rich pastures and long-rotation grazing and a conventional agriculture system comprising standard pastures and grazing techniques, across soils with low and high inputs of phosphorus fertiliser. The four treatments were established as four 2-ha farmlets of 20 paddocks between 10 December 2021 and 16 March 2023.Incoming and transmitted photosynthetically active radiation (PAR) were measured with a SunScan for every plot before and after every defoliation and once a month for all plots concurrently. Samples of pasture mass of each plot were taken by the RADE team. Radiation use efficiency was calculated from accumulated yield and intercepted PAR. Yield, intercepted PAR, radiation use efficiency, farm cover, post grazing pasture mass, and proportion of dead and weed of biomass and nitrogen content was subjected to analyses of variance and a linear regression analysis for recovery of pasture was undertaken.

The results indicate that, after the four and a half month, the regenerative system accumulated a lower yield than the conventional system (2347 kg DM/ha vs. 3354 kg/ha), a greater accumulated intercepted PAR (612 MJ/m^2 vs. 530 MJ/m^2 vs.), and a lower mean radiation use efficiency (0.389 g/MJ vs. 0.646 g/MJ). Furthermore, it was found that, in the regenerative plots, post grazing pasture mass was higher by 943 kg DM/ha, and average farm cover was higher throughout the measuring period, but rate of recovery was not different (19.74 kg DM/ha/day) when compared to the conventional pastures. A higher proportion of dead material (0.35 vs. 0.24), but lower proportion of weeds (0.03 vs. 0.013) were found in the regenerative pasture. Nitrogen content of pasture dry weight was lower for the regenerative system (2.44% vs 3.07%). Differences between fertility levels and system-fertility interaction were found to be non-significant.

The higher radiation use efficiency of the conventionally farmed plots in the RADE gave rise to the hypothesis that the rotational grazing system typically found in New Zealand agriculture is operating at a near optimum and cannot be compared to most livestock or cropping systems within other countries. However, further research is required to determine if regenerative systems could provide a higher level of yield stability for high-stress environments, such as the drought prone east coast region of New Zealand. Furthermore, there are opportunities for research on animal performance, soil carbon sequestration and on the long term implications of these multispecies regeneratively managed pastures.

Keywords: dryland, grazing, light, long-rotation grazing, multi-species pasture, phosphorus, radiation use efficiency, radiation use efficiency, regenerative agriculture, sheep production

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Chapter 1

Introduction

The public interest in agricultural practices and their environmental and social impacts has increased within the last decades (Giller *et al.*, 2017). The global food system has been described as ‘in crisis’ and ‘broken’ (Giller *et al.*, 2021) and conventional agriculture has been laid out as an issue for further investigation regarding its cost to society and the environment (Bergman *et al.*, 2022).

World population has been growing drastically within the last century (Brown & Caligari, 2011), reaching the 8 billion mark in November 2022 (United Nation, 2022). And the population is expected to continue to grow to 9.4 – 10 billion people in 2050, with a possibility of a peak around 2050 (United Nation, 2022). Additionally, the environment of agricultural farmland is changing. The severity and abundancy of extreme weather events like droughts and heavy rainfall events has been on the increase due to the impact of climate change (Acquaah, 2021). All of the above is putting a focus on agricultural production, its impact on the environment, its ability to feed a seemingly ever-growing population, and its potential to increase the efficiency of existing systems in terms of yields as well as its impact on environmental factors like soil health, biodiversity, and carbon sequestration.

Regenerative agriculture (RA) has gained a lot of interest within the last decade (Giller *et al.*, 2021). Hopes are displayed from various groups that RA will improve the impact of food production on climate change to a point where there are claims that RA is even able to reverse climate change (Grelet *et al.*, 2021; Kastner, 2016). Among the benefits ascribed to RA are improved soil health and an increase in soil carbon, an increase in biodiversity, and a solution for declining health of freshwater ecosystems and water quality (Newton *et al.*, 2020; Rowarth *et al.*, 2020; Grelet *et al.*, 2021). Kastner (2016) states that RA is able to draw billions of tons of carbon out of the atmosphere and to lock it into the soil, “*where it belongs*”.

However, other parties are more cautious of the potential impacts of RA on the global food production system. A decline in productivity is at the forefront of these worries, with the implication of a decrease in global food security (Robertson *et al.*, 2022; Manshanden *et al.*, 2023). Furthermore, there are uncertainties of how much additional carbon can be sequestered by a RA system, as the scientific understanding of carbon sequestration in soil is still limited (World Resources Institute, 2019; Manshanden *et al.*, 2023). The question is brought up what exactly RA actually seeks to regenerate (Robertson *et al.*, 2022; Giller *et al.*, 2021).

Additionally, to this day there is no singular definition of RA (Manshanden *et al.*, 2023). This can have benefits when taking “positive psychological responses” into consideration that the term of RA can have in a marketing perspective (Moot, 2023). However, the absence of a definition for RA can lead to confusion around intentions and directions, not only for farmers but also for consumers, and may cause various challenges for researches who seek to study RA systems (Newton *et al.*, 2020; O’Donoghue *et al.*, 2022).

The concept of RA first emerged in the early 1980s, when Robert Rodale created the Regenerative Agriculture Association in the USA (Grelet *et al.*, 2021). Early descriptions of RA mention the achievement of a sustainable food production by restoring resources that were degraded by conventional agriculture (CA), such as soil, water, biota, and human wellbeing (O’Donoghue *et al.*, 2022).

The New Zealand agricultural system is based largely on grazed pastures and is not directly comparable with many other cropping systems overseas, such as those in the Cornbelt of the United States where soybeans and maize are rotated on large areas unbroken by hedges or fences (Rowarth *et al.*, 2020). It is widely recognised that continues cropping can degrade agricultural soils, and that a system is required to improve their soil carbon storage, but it can be questioned whether this is the case for widespread grass/clover pasture systems in New Zealand. Therefore, the argument has taken hold that New Zealand farming systems are not depleted and are already regenerative (Grelet *et al.*, 2021). The expectation is that regenerative agriculture can increase the production of food and fibre from grassland in a sustainable manner through efficient utilisation of resources, including water, nutrients and light.

The aim of this dissertation was to investigate if regenerative agriculture can increase the radiation efficiency of grassland production. The objectives, or steps, taken to achieve this aim were:

1. To review existing literature on the effects of principles/practices of regenerative agriculture on radiation use efficiency of grassland production.

2. To collect data on grassland radiation use efficiency and explanatory variables of regenerative and conventional agriculture systems across soils with low and high inputs of phosphorus, from 4.5 months (15 February to 28 June 2023) of a new farmlet-scale experiment at Lincoln University.

3. To analyse the dataset for effects of agricultural system and phosphorus and for consistency of these effects over the timeframe.

4. To interpret the data in relation to principles of crop physiology and components of crop radiation use efficiency.

5. To make recommendations for future research and for the implementation of regenerative agriculture in dry east coast regions of New Zealand.

Chapter 2

Literature Review

2.1 Introduction

In this chapter, the principles/practices of regenerative agriculture and their effects on radiation use efficiency of grassland production are reviewed (Objective 1). The variability of the term "regenerative agriculture" is discussed, and common practices that it often entails and their effect on light interception are looked at in detail. Furthermore, an overview of plant and light interactions is provided.

2.2 Regenerative Agriculture – origins and modern interpretations of the farming system

Regenerative agriculture has gained a lot of attention within the last decades and is often proposed to be a more sustainable alternative to the conventional agricultural food system (Shreefel *et al.*, 2020). However, there is no universal scientific definition that states what regenerative agriculture is composed of (Shreefel *et al.*, 2020). Different agronomists and scientists have interpreted regenerative agriculture in different ways, which are summarized below.

Robert Rodale defined regenerative agriculture in 1983, as a practice that "at increasing levels of productivity, increases our land and soil biological production base" (Giller *et al.*, 2021). Within the same year, the director of the Rodale Research Centre, Richard Harwood, published an international overview of regenerative agriculture. Harwood (1983), Director of Rodale Research Centre at the time, released an international overview of RA, where he stated that RA seeks to produce "*highly nutritional food, free from biocides, at high yields*", while increasing soil productivity. However, this should be done without the use of "*substances which disrupt biological structuring of the farming system*", for example synthetic fertiliser at that time. Additionally, Harwood (1983) emphasizes social aspects of regenerative agriculture, including that "*agricultural production should generate increased levels employment*" and the need for "*an intimate relationship between manager/participants of the system and the system itself*". A summary of the overview of RA by Harwood (1983) is presented in Table 2.1.

Francis *et al.* (1986) described a regenerative farming system as being "*characterized by successive cycles of change in the crop and livestock production environment*", with the idea that certain cycles would create ideal conditions for certain successor cycles (Figure 2.1). The expected outcomes of a rotational system like this may include improved soil physical properties, higher turnover rates of organic matter, e net upward nutrient movement in the soil, an increase as well as a change in the soil biological activity, and an increase in the labile fraction of soil organic matter (Francis *et al.*, 1986). Common farming practices of a regenerative system as described by Francis *et al.* (1986), adapted from Harwood (1984) are summarized in Table 2.2.

Table 2.1: The Regenerative Agriculture Philosophy as presented by Harwood (1983), summarized by Giller *et al.* (2021).

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Figure 2.1: Overview of the biological structuring of a regenerative agricultural system, with emphasis on crop – animal – family interdependencies. Adapted from Francis *et al.* (1986)

Table 2.2: Regenerative farming practices. (Francis *et al.*, 1986; Harwood, 1984)

- Crop rotations that include deep rooted crops
- Highly soluble nutrient sources must be avoided
- Minimum tillage or a disk or chisel plow are to replace the moldboard plow
- Application of nutrients onto sod crops, to maximise nutrient uptake
- Cover crops are to follow major cash crops as to enhance the uptake and recycling of soluble nutrients
- Maintenance of crop residues to minimize erosion. Reduce soil crusting, and decrease evaporation

More recently, The Carbon Underground (2017) have tried to create a universal definition of regenerative agriculture which has been signed and supported by hundreds of scientist and organisations. Within that definition, regenerative agriculture is described as “farming and grazing practices that, among other benefits, reverse climate change by rebuilding soil organic matter and restoring degraded soil biodiversity – resulting in both carbon drawdown and improving the water cycle”. Furthermore, The Carbon Underground (2017) describes regenerative agriculture as a management practice that enhances photosynthesis in plants, which in turn is expected to “close the carbon cycle, and build soil health, crop resilience and nutrient density". The practices described by The Carbon Underground (2017) that are used within regenerative agriculture include no-till/minimum tillage, multispecies cover crops, crop rotations, inoculation of soils with compost, borders planted for beneficial insects, and "well-managed grazing practices". Regenerative Agriculture practices do not include monocultures, low biodiversity, soil degrading practices, feed lots and confined animal feeding systems.

Schreefel *et al.* (2020) reviewed 28 studies to compare convergence and divergence of definitions of regenerative agriculture in peer review papers. Convergence was found among thirteen objectives and seven themes for activities (Figure 2.2). Seymour (2021) has conducted farm visits and interviews with farmers in Canterbury, Otago, and Southland, who are involved with regenerative agriculture, where she defined regenerative agriculture as "a systems design approach to agriculture that is a step beyond sustainable", meaning "to be regenerative is to continually improve the health of ecosystems".

Some of the most common activities considered to be engrained in RA are further discussed in this chapter.

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Figure 2.2: Common core themes of regenerative agriculture. Number in brackets represent the number of search records. (Schreefel *et al.*, 2020)

2.2.1 Multiple species pasture mixtures

Multi-species pastures in regenerative agriculture are based on the principle of creating a more biodiverse farming environment and are thought to impact the diversity of microbial populations, insects, plants, birds, and genetics within the system (Grelet *et al.*, 2021). This can also include the strategic use of trees in the landscape. Multispecies pastures are commonly characterized by a combination of various grasses, legumes, and herbs (Goh & Bruce, 2005). Goh & Bruce (2005) investigated different multi-species pastures, including mixtures of ten, twelve, and seventeen species, and a ryegrass (*Lolium perenne*) / white clover (*Trifolium repens*) control pasture in irrigated and dryland environments in mid-Canterbury, New Zealand over a one year period. No significant difference in dry matter (DM) yield between the multi-species pastures and the ryegrass / white clover pasture under dryland conditions was found. Under irrigation, the multi-species pastures were found to yield significantly higher compared to the ryegrass / white clover pasture. However, the daily DM yield of multi-species pastures exceeded those of the ryegrass / white clover pasture significantly (Figure 2.3) (Goh & Bruce, 2005). Similarly, Harris (1968) came to the conclusion that maximum plant production could be achieved with mixtures of species as opposed to monocultures, as "*one species of a mixture may profit by association with the other species to such an extent that its yield in mixture is greater than in monoculture*". This was associated with the nitrogen fixation by clover in a mixed pasture which becomes available to grasses and/or herbs and allows them to become more competitive (Harris, 1968).

Black et al (2017) conducted an experiment including nineteen seed mixtures based on four species, perennial ryegrass, plantain (*Plantago lanceolata*), white clover and red clover (*Trifolium pratense*), to investigate the optimal mixture for maximum DM production under irrigated conditions in mid-Canterbury, New Zealand. They found that a combination of three species was ideal for pasture production and that the highest yield was achieved by a seed mixture of 0.25% ryegrass, 0.28% plantain and 0.47% red clover within the first two years of the experiment. Pairwise interactions were found between species which resulted in increased annual yields, within the first two years of the experiment. Likewise, pasture mixtures of caucasian clover, white clover, and perennial ryegrass sown in 1999 (three monocultures, three dual mixtures and one containing all three species) were investigated by Black & Lucas (2018) over five years. They found an increase in yield for the white clover / ryegrass pasture as well as the pasture containing all three species over monocultures in all five years, and an increase in yield for the caucasian / ryegrass mixture above that of its constituent monoculture species in years three to six (Figure 2.4). However, there was no yield benefit from the three species mixture above that of the white clover / ryegrass or that of the white clover / ryegrass mixtures (Black & Lucas, 2018).

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Figure 2.3: Daily dry matter yields of multiple species pastures (MSP) and ryegrass / clover pastures und dryland and under irrigated conditions. NS, not significant; Bars represent $LSD_{0.05}$ (Goh & Bruce, 2005)

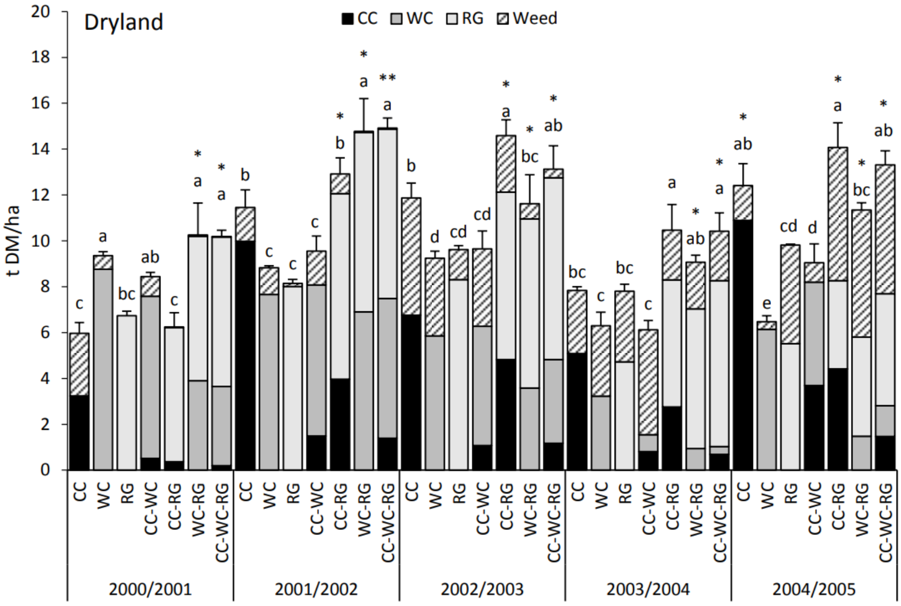

Figure 2.4: Dry matter (DM) yield of monocultures and pasture mixtures containing Caucasian clover (CC), and/or white clover (WC) and/or perennial ryegrass (RG) over five years at Lincoln University. Total yields within year with different letters are significantly different (*P<0.05, **P<0.01, ***P<0.00). (Black & Lucas, 2018)

2.2.2 Prolonged rotation grazing systems

A longer rotation of livestock at a higher stocking density with more frequent shifts is also referred to as "adaptive grazing" and the idea is to mimic the behaviour of wild herbivores and allow longer rest periods for pastures (Machmuller & Dillon; 2021, White, 2020). Some of the benefits that are expected to result from adaptive grazing are to keep the pasture at the highest photosynthesis rate and highest root growth, which in turn is thought to maximise soil carbon sequestration (Cusworth *et al.*, 2022). Furthermore, the pasture and manure are expected to be partly trampled into the ground, which then improves soil mineral content and creates habitat diversity for different insect and worm species (Cusworth *et al.*, 2022; Flack & Karreman, 2016).

From the farmers perspective productive pastures are the key component which impact a profitable farming system (Donaghy *et al.*, 2021; Beca, 2020). From a plant focused perspective, farmers are recommended to graze paddocks close to the onset of canopy closure, which for a ryegrass based pastures sits at a pasture mass of about 2600 – 3200 kg DM/ha depending on the ploidy, and if the pasture is annual or perennial (McCarthy *et al.* 2014; Donaghy *et al.*, 2021). Longer rotations have been found to be beneficial in more stressful environments as it maximises the energy reserves of plants, which is associated with an increase in tillering and root production, and in turn pasture persistency and survival. Furthermore, Donaghy *et al.* (1997) saw no impact of a longer grazing rotation during times of less stress. However, within the pastures that were under a longer rotation grazing system, the survival of perennial ryegrass was higher in the following harsh summer, showing that it was possible to build resilience before a time where environmental stressors increased (Donaghy *et al.*, 2021; Donaghy *et al.*, 1997).

2.2.3 The use of fertilisers

> *"Substances which disrupt biological structuring of the farming system (such as present-day synthetic fertilizers) should not be used"* (Giller *et al.*, 2021; Harwood, 1983).

The use of fertilisers is strongly discouraged in RA practices, especially nitrogen (N) fertiliser is considered to have detrimental effects and the use of legumes in pastures is encouraged as a means to replace artificial N fertiliser with N fixation (Merfield, 2019). Suggestions are made that the use of synthetic fertilisers with the aim to achieve high yields in conventional farming has depleted the soil of nutrients (Rowarth *et al.*, 2020). Other concerns about the conventional use of fertilisers have been expressed relating to nutrient leakage, especially that of N and phosphorus (P) fertilisers which can cause an increase of these nutrients in waterbodies and reduce the quality of freshwater and endanger native aquatic wildlife (Monaghan *et al.*, 2005).

In New Zealand, extensive research has resulted in a soil testing system that is suitable for the relatively recent soils and confirmed “Liebig’s Law of the Minimum” for plant yield, which states that growth is limited by the scarcest resource (Rowarth *et al.*, 2020; Niles *et al.*, 2014). In terms of N fixation by legumes, it has been shown by Sinclair *et al.* (1996b) that sulphur (S) and P applications are increasing the % of N fixation of white clover on New Zealand soils. Sinclair *et al.* (1996a) describe a balanced nutrition in white clover which combines the use of P and S fertiliser and enables farmers to find economically optimal rates to achieve a high clover DM yield (Figure 2.5).

Monaghan *et al.*, (2005) investigated the effects of nitrogen fertiliser inputs in Southland, New Zealand, and found that the applications of nitrogen fertiliser did increase DM pasture production. In Monaghan *et al.* (2005) study the effect of an approaching plateau of the effect of increasing fertiliser applications can be observed again as well, with the efficiency of N fertiliser decreasing as the level of N input was increased. However, they also found a decrease in clover content with increasing N fertiliser application, which is similar to what other studies have reported (Monaghan *et al.*, 2005; Whitehead 1995) (Table 2.3).

Since July 2021 there has been a cap of 190 kg/ha/yr for N fertiliser applications in New Zealand (Ministry for the Environment, 2021). When compared with Monaghan *et al.* (2005) findings (Figure 2.6) this N fertiliser cap paired with best management practices, such as not applying fertiliser before a major rainfall event, will minimize nitrate N in drinking water.

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Figure 2.5: Clover DM yields in response to phosphorus (P) and sulphur (S), summed over 2 years. (Sinclair *et al.*, 1996a)

Table 2.3: Annual grass, clover, and total dry matter production at four rates of N fertiliser. *, P < 0 .05; **, P < 0.01; ***, P < 0.001. (Monaghan *et al.*, 2005)

Kg N/ha	Grass (kg/ha)	Clover (kg/ha)	Total (kg/ha)	Pasture response to N (kg DM per kg N applied)	Annual increase (%) in yield over 0N
0	9203	1546	10 749		
100	10 984	1245	12 229	14.8	13.8
200	12 325	1009	13 334	12.9	24
400	13 593	810	14 403	9.1	34
SED	585	102	625		
P	***	**	**		

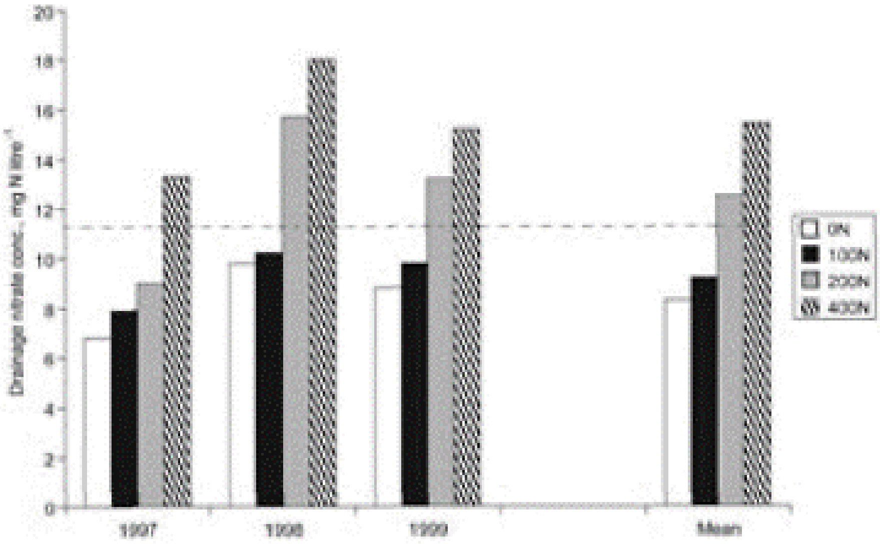

Figure 2.6: Nitrate N in drinking water in response to four N fertiliser applications (0, 100, 200, 400). Dashed line represents New Zealand standard for nitrateN in drinking water (11.3 mg N/litre). (Monaghan *et al.*, 2005)

2.2.4 Performance of regenerative farming systems

LaCanne & Lundgren (2018) conducted a study in the United States, comparing regenerative and conventional corn (Zea mays L.) production systems. The regenerative farming systems LaCanne & Lundgren investigated, were never tilled, with no use of insecticides, grazed livestock on their cropland and used multispecies mixed cover crops. The farms considered conventional in their study had to use tillage at least annually, used insecticides, and only farmed cash crops. The factors assessed for the plots of each framing system were, corn yield and profit, soil organic matter, and insect pest populations. LaCanne & Lundgren (2018) found that the regenerative systems had a yield reduction of

29%, but an increase in profitability of 70%, compared to the conventional cornfields. Furthermore, they found a 10 fold higher corn pest abundance on farms that were treated with insecticides, compared to regenerative farms (Figure 2.7).

However, the increase in profitability of the regenerative system in the LaCanne & Lundgren (2018) study was due to various factors, including lower seed and fertiliser costs, as well as receiving an organic premium for their crop. It should be noted that an organic premium would not be a given for regenerative farms in New Zealand, if they are not certified as an organic farm, which would be a process of up to 3 years and would come with certification fees (MPI, 2023; Organic Farm NZ, 2023; AsureQuality, 2018).

Regenerative Agriculture and the efficiency of light interception

An example of how a potential regenerative system could effectively capture most of the light during the entire year is mentioned by Francis *et al.* (1986). Francis *et al.* describe a three crop relay system used in South America, including potatoes that are planted in January, maize in April, and beans in July, with the potatoes being harvested in June, and the maize and beans together in December or January. Other multiple cropping systems are mentioned that are described as more effective than monoculture systems. However, there has been no research into light interception or radiation use efficiency of regenerative agricultural systems so far.

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Figure 2.7: Mean corn pest abundance per m^2 in cornfields in regenerative agriculture systems and conventional agriculture systems. Pests assessed were corn rootworm adults, European corn borers, Western bean cutworm, other caterpillars, and aphids. (LaCanne & Lundgren, 2018).

2.2.5 Conventional Agriculture – what are the differnces and similarities in a New Zealand context

The term conventional agriculture is mostly used in relation to “alternative” agriculture practices. Therefore, “Conventional agriculture” is often connected with undesirable attributes, for example environmental destruction, being unsustainable, greenhouse gas emitting, and being dominated by corporate interests (Sumberg & Giller, 2022). De Ponti *et al.* (2012) compared conventional agriculture to organic agriculture and therefore defined conventional agriculture as “any agricultural system in which chemical inputs are used”. However, as organic agriculture differs from regenerative agriculture, the definition for conventional agriculture in this paper is not as simply put. O’Donoghue *et al.* (2022) refer to conventional agriculture as “the dominant system of production in a region”. This definition is more fitting for this paper and henceforward the term “conventional agriculture” will be linked to the dominating agricultural practices in New Zealand at this time.

In New Zealand, pastoral agriculture plays a crucial role in the primary sector, which is responsible for over 50% of total export earnings (Keller *et al.*, 2014; Caradus *et al.*, 2023). 7.4 million hectares of the rural landscape is made up of grassland, supporting dairy, sheep, beef, and deer farming (B+LNZ, 2921; Caradus *et al.*, 2023). Turner *et al.* (2020) states that New Zealand’s agricultural system reflects institutional, organisational, and technological arrangements, which are focused on increasing productivity while reducing the effect of agriculture on the environment. However, it needs to be taken into consideration that, in New Zealand as well as globally, there is diversity among conventional farmers and their farming systems (Fairweather *et al.*, 2009). In conventional agriculture in New Zealand, best management practices (BMPs) are often mentioned (Brown *et al.*, 2019). An example of best management practices can be found in the Beef & Lamb “Farm Plan – Environment Module”, which includes managing soil health, freshwater ecosystem health, integrating native biodiversity, responding to climate change, waste and chemical management, forage cropping (with an emphasis on winter grazing) (Beef & Lamb, n.d.).

2.3 Plant and Light Interactions – why do they matter?

One of the most crucial factors driving agricultural production is light. Plants can capture light via photosynthesis and convert it into stored chemical energy, a crucial process for maintaining life on our planet (Ullah *et al.*, 2019). The term photosynthesis can be translated to “synthesis using light” (Taiz & Zeiger, 2002). Light is what fuels photosynthesis and is the most limiting factor for plant growth and dry matter accumulation, when water and nutrients are not limited. The availability of light has a crucial influence on plant growth (Sinclair & Muchow, 1999). However, only a proportion of incoming sunlight is intercepted by a plant during its lifecycle (Sinclair & Muchow, 1999). The efficiency with which plants absorb light and produce dry matter is called radiation use efficiency (RUE) (Ullah *et al.*, 2019). The improvement of RUE of crops and pastures paired with the evaluation of RUE between different systems, could provide a necessary step towards global food security.

The light of the sun is the most crucial energy component for life on Earth (Schulze *et al.*, 2019). The only process of biological importance that can harvest this energy is photosynthesis, which can literally be translated to “synthesis using light” (Taiz & Zeiger, 2002). Sunlight is therefore one of the most important environmental factors for plants, the basis for growth, and a key component in the process of providing chemical energy and oxygen to ecosystems (Schulze *et al.*, 2019). And growth is a direct result of a plants ability to absorb light energy and, through conversion into reductive chemical energy, fix carbon dioxide (Attridge, 1990).

Plants can harness the radiant energy (PAR) of the sun and change it into chemical energy (carbohydrates) though the process of photosynthesis (White & Hodgson, 1999). Carbon dioxide (CO_2) is removed from the air and used within the Calvin cycle. This process involves a series of chemical reactions, with PAR being captured by chlorophyll and other pigments in the chloroplast, and water being split into oxygen (O_2) and hydrogen ions (H^+) via a series of reduction/oxidation reactions (White & Hodgson, 1999). Therefore, plants require red and blue wavelength light, for the purpose of photosynthesis (Attridge, 1990). Photosynthetically active radiation (PAR) is between wavelengths 400nm and 700nm and is approximately 50% of the incoming radiation from the sun (White & Hodgson, 1999). Some of the incoming radiation is reflected, some absorbed, and some transmitted (Attridge, 1990).

When sunlight reaches the leaf of a plant, excitation of chlorophyll by photons sets of an electron transfer chain which produces the high energy compounds adenosine triphosphate (ATP) and reduces nicotinamide adenine dinucleotide phosphate (NADPH) (Schulze *et al.*, 2019). These compounds are then used in the production of sugars in the carbon fixation reactions (Taiz & Zeiger, 2002).

Most pasture species that are used within New Zealand are C_3 plants, which use an enzyme called rubisco (Ribulose-1,5-bisphosphate carboxylase/oxygenase) for carbon fixation (White & Hodgson, 1999). This process of photosynthesis is extremely inefficient, with an energy use of approximately 0.9% on a PAR basis, in Canterbury, with an average of 5210 MJ/m^2/year of sunlight and a yield of 1400 g DM / m^2 per year (White & Hodgson, 1999). Maximum efficiency of C_3 plants is estimated to be around 6% on an incident PAR basis. This efficiency is influenced by various factors, such as losses due to pest disease, reduced photosynthesis due to increased temperatures, nutrient or water stress, increased respiration losses, and management factors such as sowing date affecting the time a crop has to capture sunlight (White & Hodgson, 1999). Furthermore, the amount of light that a leaf can intercept can vary with latitude, season, time of day, cloud cover, leaf inclination, and aspect (Attridge, 1990). However, for pastures, as well as for arable crops and perennial tree crops, a linear relationship exists between intercepted solar radiation and yield (Figure 2.8) (White & Hodgson, 1999).

There are various ways farmers can increase the amount of sunlight a pasture or crop can intercept (White & Hodgson, 1999). These include sowing date, plant population, irrigation, amount and timing of fertilizer applications, herbicide use to decrease interspecific competition for light, and pesticide use to control pests (White & Hodgson, 1999). There is no scientific evidence that regenerative agriculture will positively or negatively affect the amount of PAR a pasture can intercept, opening up an opportunity for research in this area.

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Figure 2.8: Linear relationship between absorbed radiation and accumulated dry matter of lentils in Canterbury, New Zealand (White & Hodgson, 1999).

2.3.1 Radiation Use Efficiency

By the process of photosynthesis a plant can store a fraction of the absorbed radiant energy as carbohydrates (Monteith, 1977). Radiation use efficiency (RUE) is the efficiency with which a crop or pasture absorbs light (PAR) and produces dry matter (Ullah *et al.*, 2019). It was in the 1960s when field experiments linked the vegetative growth of crops in terms of accumulated dry matter (DM) to intercepted radiation (Warren Wilson, 1967; Monteith, 1972; Monteith 1977). In 1977, Monteith (1977) defined the efficiency of crop production as a ratio of energy output, in terms of carbohydrate, to energy input, in terms of solar radiation, and presented the first steps which later led to prediction of radiation use efficiency.

To estimate RUE, the ratio of accumulated biomass per unit of intercepted solar radiation needs to be measured (Ullah *et al.*, 2019). Linearly regressing accumulated dry matter versus cumulative intercepted PAR is also a way to calculate RUE, with the slope of the regression line representing RUE (Ullah *et al.*, 2019).

Variability in soil fertility, crop management practices, the vegetative structure of crops, climatic conditions, and various stress factors, can all cause a variation in RUE (Figure 2.9) (Blanco *et al.*, 2020; Ullah *et al.*, 2019; Rouphael & Colla, 2005). Furthermore, as there is a linear relationship between dry matter production and the amount of solar radiation that is intercepted, canopy architecture and foliage structure will influence canopy light availability (Ullah *et al.*, 2019). Therefore, leaf area index (LAI) and leaf mass per unit area will have a direct impact on RUE (Ullah *et al.*, 2019).

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Figure 2.9: Major factors governing the potential radiation use efficiency (RUE) (Blanco *et al.*, 2020).

2.3.2 Specific Leaf Area

Specific Leaf Area (SLA) is the ratio of leaf area to leaf weight in m^2/kg. SLA can determine the productivity of plants and is driven by increases in sugars and starch, following increasing rates of photosynthesis (Gong & Gao, 2019). Annual crop plants can reach a SLA of 23.6m^2/kg whereas evergreen conifers have a SLA of typically around 4.1 m^2/kg (Schulze *et al.*, 2019). In their study on SLA of 631 grassland species in different environments in China, Liu *et al.* (2021) found a range of SLA from 0.9 to 58.9 m^2/kg.

Species with a low SLA usually have low rates of CO_2 assimilation and are able to endure drought stress to greater degree (Schulze *et al.*, 2019). In contrast, plants with a higher SLA assimilate large quantities of CO_2 and are less stress tolerant. An increase in a plants SLA can enhance its ability to withstand stressful conditions like drought, the concentration of nitrogen (N) and other nutrients increases, and the ratio of assimilating cells to the transpiring surface increases (Schulze *et al.*, 2019).

2.4 Conclusion

The review of scientific literature on RA highlights the novelty of this agricultural concept, and the limited amount of research that has so far been undertaken. Key findings include the absence of a universal definition of RA, but that it commonly include practices that share the aim of carbon sequestration in the soil and to increase biodiveristy. Practices usually included in the system are minimum tillage, mixed species pastures, a prologed grazing rotation, and no use of synthetic fertilisers or herbicides. This literature review also shows that New Zealand pastoral farming systems and regnerative agricultural prcactices are not as different as cropping systems in other countries are to regenerative agriculture. More research is needed on regenerative agriculture to investigate this farming systems efficiency and economical, environmental, and social impact.

Chapter 3

Materials and Methods

The materials and methods used to collect and analyse data on the radiation use efficiency of grassland production for regenerative and conventional agriculture systems across soils with low and high inputs of phosphorus fertiliser (Objectives 2 and 3) are described in this chapter.

3.1 Climate

Climate data was sourced from the NIWA climate station at Broadfield, approximately 2 km north of the RADE, and is reported over the whole agricultural year. Over the period of this dissertation, from the start of February to the end of June, rainfall was higher at an average of 69.1 mm / month compared to the long-term mean of 53.0 mm / month. Potential evapotranspiration (PET) was similar to the long-term mean over the whole period of this dissertation (Figure 3.1). Average mean air temperature from February to the end of June was higher at 13.6°C compared to the long term mean of 11.7°C (Figure 3.2).

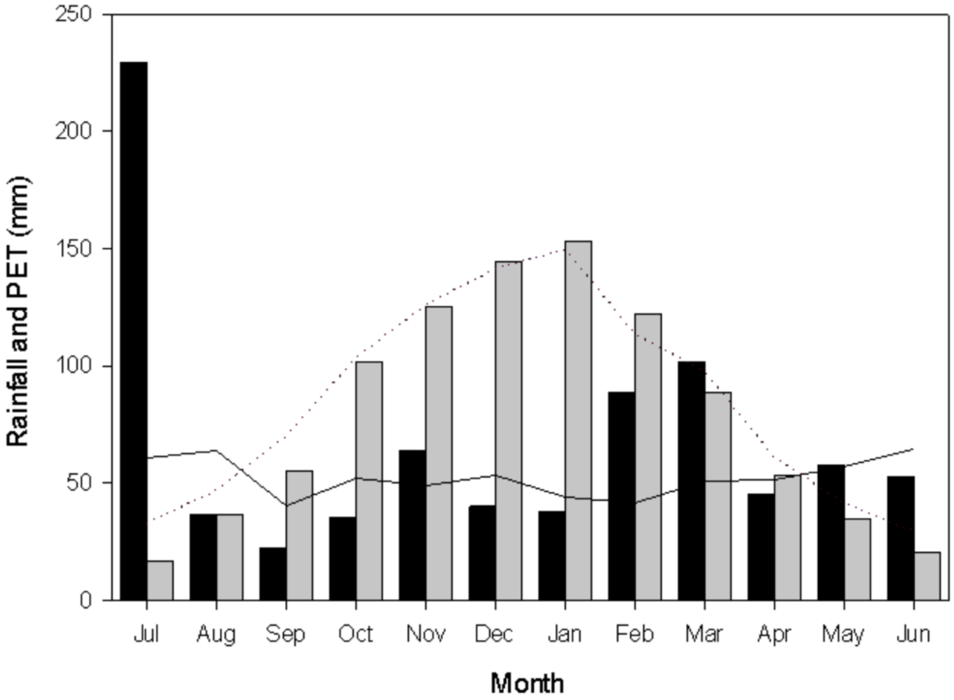

Figure 3.1: Average rainfall ■ and potential evapotranspiration (PET) ▨ per month in 2022-2023, and long-term means of rainfall —— and PET ---- (1975 – 2015) in mm.

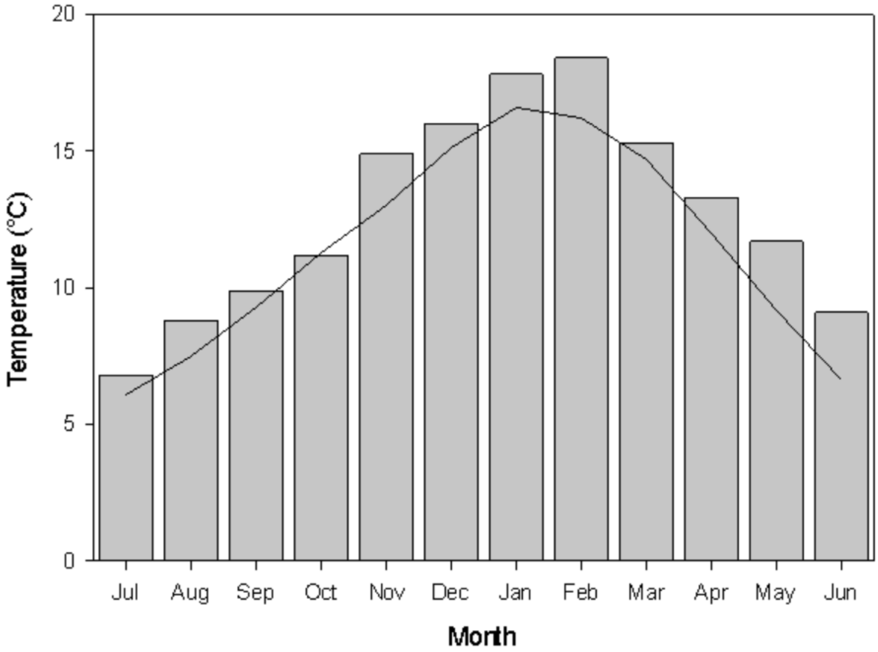

Figure 3.2: Average temperature (°C) per month ■ (2022-2023) and long term mean of temperature (°C) — (1975 – 2015).

3.2 Experimental Site

The RADE is located in paddocks H11, H12, H13, H14, H17 and H19 at the Lincoln University Horticulture Research Area, Canterbury. All paddocks are flat agricultural land. The soil type is a Templeton silt loam (Typic Immature Pallic Soil) and varies in depth to the gravel level. Templeton silt loam soil drains moderately well and has a moderate vulnerability to waterlogging in non-irrigated conditions, and a high water holding capacity. This soil is also considered to have a high structural vulnerability, a low potential for N leaching and a low (23%) topsoil phosphorus retention (Landcare Research New Zealand Limited, 2023) (Figure 3.3). Soil test results from the previous years can be found in Table 3.1.

Prior to the RADE, H11 was in a cocksfoot based multispecies pasture mix for four years, H12 was in Italian ryegrass (Lolium multiflorum) for two years, and H13 was in a cocksfoot based multispecies pasture mix for two years. H14 was in a lucerne (Medicago sativa) monoculture for nine year, but from September 2021 onwards was in a fallow for six month until the start of the RADE. H17 was set up in 1996 as a comparison for two different pastures over two different soil fertility levels (Olsen P 10 and 20 mg/kg) in thirty-two 0.04 ha plots over two 4^2 Latin squares. The two levels of soil fertility have been maintained since. Prior to the RADE, over the winter and spring period in 2021, H17 was in greenfeed oats (*Avena sativa*). H19 was in Italian ryegrass (Lolium multiflorum) (west side) and in perennial ryegrass (Lolium perenne) and white clover (Trifolium repens) (east side) for three years prior to the RADE.

Between April and November 2021 the high fertility plots in Latin square 1 (H17) and Latin square 2 (H19) were fertilized with 400 kg/ha of Superphosphate, 350 kg/ha of Sulphur Super 20 and Aglime and the low fertility plots received 50 kg/ha of Sulphur Super 20 and Aglime. In Latin square 3 (H13 and 14) the high fertility plots were fertilised with 400 kg/ha of Superphosphate and the low fertility plots received no fertiliser on 7-8 March 2022 (Table 3.2).

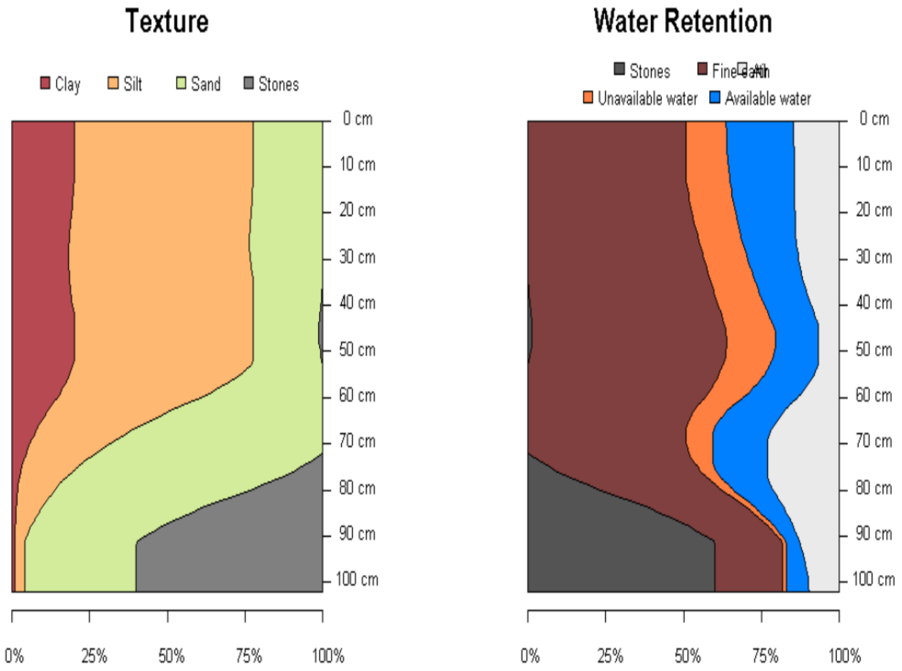

Figure 3.3: Soil texture and water retention to 100cm. (Landcare Research New Zealand Limited, 2023)

Table 3.1: Soil test results (H – High fertility, L – Low fertility)

Sample Name	Sample Date	Core length (cm)	pH	Olsen Sol. P (ug/mL)	CEC (me/100g)	Base Saturation (%)			
						Calcium	Magnesium	Potassium	Sodium
H11	14/9/22	7.5	6.3	17	15	53.7	8.2	4.6	1.0
H12	14/9/22	7.5	6.0	12	20	46.4	6.6	5.4	<1
H17 L	18/11/21	7.5	5.4	8	14	37	5.4	3.1	<1
H17 H	18/11/21	7.5	5.4	15	15	42.2	5.5	3.0	1.1
H19 L	18/11/21	7.5	5.6	8	14	34.1	5.9	1.7	1.6
H19 H	18/11/21	7.5	5.5	10	14	33.1	5.0	1.9	1.0

Table 3.2: Fertiliser applications (LSQ: Latin square, Fert.: fertility of the plot)

Date	Block	Plot	LSQ	Fert.	Plot area	Product	N %	P %	K %	S %	Ca %	Fert kg/plot
16/04/2021	H17	3, 4, 5, 6, 9, 12, 14, 15	1	H	0.087	Super-phosphate	0	9	0	11	20	17.4
30/07/2021	H19	20, 24, 27, 31	2	H	0.087	Super-phosphate	0	9	0	11	20	17.4
08/10/2021	H19	18, 22, 25, 29	2	H	0.087	Super-phosphate	0	9	0	11	20	17.4
08/11/2021	H17	1 to 16	1	H & L	0.087	Aglime	0	0	0	0		522
08/11/2021	H19	17 to 32	2	H & L	0.087	Aglime	0	0	0	0		174
30/11/2021	H17	3, 4, 5, 6, 9, 12, 14, 15	1	H	0.087	Sulphur Super 20	0	8	0	20.6	18	30.45
30/11/2021	H19	18, 20, 22, 24, 25, 27, 29, 31	2	H	0.087	Sulphur Super 20	0	8	0	20.6	18	30.45
01/12/2021	H17	1, 2, 7, 8, 10, 11, 13, 16	1	L	0.087	Sulphur Super 20	0	8	0	20.6	18	4.35
01/12/2021	H19	17, 19, 21, 23 26, 28, 30, 32	2	L	0.087	Sulphur Super 20	0	8	0	20.6	18	4.35
07/03/2022	H13/14	42, 44, 46, 47	3	H	0.132	Super-phosphate	0	9	0	11	20	52.8
08/03/2022	H13/14	33, 34, 39, 40, 46	3	H	0.132	Super-phosphate	0	9	0	11	20	52.8
14/04/2022	H13/14	45, 46	3	H	0.132	Urea	46	0	0	0	0	14.3484
03/10/2022	H11/12N	49, 51, 52, 54, 55, 56, 57, 59, 60, 62, 63, 64	4	H & L	0.089	Super-phosphate	0	9	0	11	20	22.25
03/10/2022	H11/12N	50, 53, 58, 61	4	L	0.089	Sulphur 90	0	0	0	90	0	1.78
14/10/2021	H17	3, 4, 5, 6, 9, 12, 14, 15	1	H	0.087	Super-phosphate	0	9	0	11	20	17.4
14/10/2021	H19	18, 20, 22, 24, 25, 27, 29, 31	2	H	0.087	Super-phosphate	0	9	0	11	20	17.4

3.3 Experimental design

The experiment is set up over five 4x4 Latin squares, with the treatments being two different systems of agricultural management, conventional agriculture and regenerative agriculture, and two levels of soil fertility, high and low. The soil fertility is based on Olsen P values, with the low fertility plots being kept at an Olsen P of 10 and the high fertility plots having an Olsen P of 20. Fertiliser is applied accordingly, to maintain the levels of high and low fertility.

A 2^2 factorial of these treatments was randomised and replicated over the five Latin squares, with sixteen plots per Latin square, adding up to eighty plots in total (Figure 3.4.). For this dissertation, measurements were taken within the first four Latin squares. The plots size differs between Latin squares, but averages to 0.097 ha per plot overall and 0.099 ha per plot for the first four Latin squares. All plots are fenced and fitted with water troughs. There was no irrigation, meaning all of the experiment was rain fed. During the establishment phase the plots were grazed by stud Coopworth hoggets and were then replaced on the 1st of April 2023 by Bohepe ewes. The regenerative plots are in pastures made up of twelve species mixtures, based on industry advice. The conventional system is based on New Zealand specific, best practice farming approaches and includes plots of lucerne monoculture and subterranean clover (*Trifolium subterraneum*) / cocksfoot (*Dactylis glomerata)* pastures with two different cultivars of subterranean clover (‘Denmark’ and ‘Narrikup’), as well as an annual ryegrass (*Lolium multiflorum*) forage crop. Consultation of the RADE Technical Advisory Group (TAG) has been sought to advice for any decisions regarding plant, soil, animal, and management protocols.

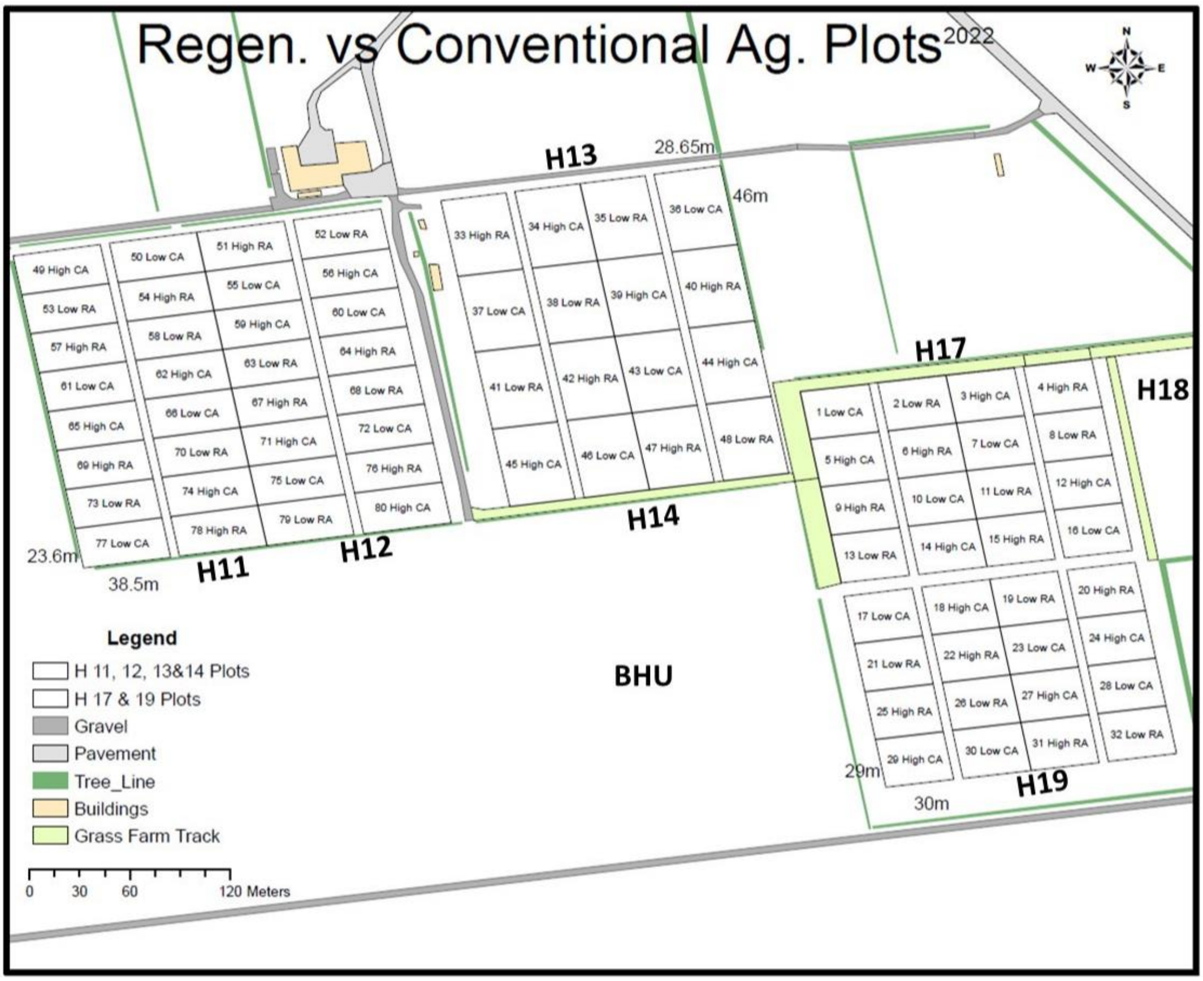

Figure 3.4: Plot Plan of the Regenerative Agricultural Dryland Experiment at Lincoln University

3.3.1 Pasture

Details of species in each pasture in each Latin square can be found in Table 3.3. The two forage types in Latin Square one and two were lucerne monoculture for the conventional plots and a twelve species pasture mixture that included lucerne for the regenerative plots. The lucerne cultivar used in Latin square one was Kaituna and the lucerne cultivar used in Latin square two was Takahe. In Latin square three, the conventional pasture type was made up of cocksfoot (Greenly II) and subterranean clover (Denmark & Narrikup), and the regenerative pasture was made up of twelve species but did not include lucerne. However, plot 45 to 48 in Latin square three were converted to supplementary winter feed crops and 41 to 44 to 12-species mix including balansa clover for the regenerative plots and to subterranean clover / cocksfoot pasture mixture for the conventional plots. Conventional plots 43, 44, 45 and 46 were sprayed (Roundup Ultra Max 2 L/ha in 200 L of water/ha) on the 21st of February 2023, cultivated in the following week, and drilled on the 17th of March 2023 to establish conventional winterfeed crops. Regenerative plots 41, 42, 47 and 48 were grazed hard before direct drilling an eight species green feed multispecies forage crop on the 17th of March 2023.

Table 3.3: Regenerative and Conventional Pasture Mixture over Latin square 1-4

Latins square	System	Species		Cultivar	Rate (kg/ha)
1	**Regenerative**	Chicory	*Cichorium intybus*	Choice	1
		Cocksfoot	*D. glomerata*	Safin	0.5
		Lucerne	*Medicago sativa*	Kaituna	6
		Meadow Fescue	*Festuca pratensis*	Oakdon	4
		Phalaris	*Phalaris aquatica*	Mate	0.3
		Plantain	*P. lanceolata*	Captain	0.5
		Prairie Grass	*B. willdenowii*	Jeronimo	5
		Red Clover	*T. pratense*	Amigain	1
		Subterranean Clover	*T. subterraneum*	Woogenellup	1
		Tall Fescue	*F. arundinceae*	Hummer	4
		Timothy	*Phleum pratense*	WGB23587	2
		White Clover	*Trifolium repens*	Legacy	0.3
	Conventional	Lucerne	*Medicago sativa*	Kaituna	15
2	**Regenerative**	Chicory	*Cichorium intybus*	Choice	1
		Cocksfoot	*D. glomerata*	Safin	0.5
		Lucerne	*Medicago sativa*	Takahe	6
		Meadow Fescue	*Festuca pratensis*	Oakdon	4
		Phalaris	*Phalaris aquatica*	Mate	0.3
		Plantain	*P. lanceolata*	Captain	0.5
		Prairie Grass	*B. willdenowii*	Jeronimo	5
		Red Clover	*T. pratense*	Amigain	1
		Subterranean Clover	*T. subterraneum*	Woogenellup	1
		Tall Fescue	*F. arundinceae*	Hummer	4

		Timothy	*Phleum pratense*	WGB23587	2
		White Clover	*Trifolium repens*	Legacy	0.3
	Conventional	Lucerne	*Medicago sativa*	Takahe	15
3 **(33-44)**	**Regenerative**	Balansa clover	*T. michelianum*	Taipan	1
		Chicory	*C. intybus*	Choice	1
		Cocksfoot	*D. glomerata*	Safin	0.5
		Meadow Fescue	*Festuca pratensis*	Oakdon	3
		Phalaris	*Phalaris aquatica*	Mate	0.3
		Plantain	*P. lanceolata*	Captain	0.5
		Prairie Grass	*B. willdenowii*	Jeronimo	5
		Red Clover	*T. pratense*	Amigain	2
		Subterranean Clover	*T. subterraneum*	Woogenellup	1
		Tall Fescue	*F. arundinceae*	Hummer	5
		Timothy	*Phleum pratense*	WGB23587	2
		White Clover	*Trifolium repens*	Legacy	0.5
	Conventional	Cocksfoot	*D. glomerata*	Greenly II	4
		Subterranean Clover	*T. subterraneum*	Denmark	10
		Subterranean Clover	*T. subterraneum*	Narrikup	16
3 **Winterfeed** **(45-48)**	**Regenerative**	Annual ryegrass	*L. multiflorum*	Devour	5
		Balansa Clover	*T. michelianum*	Taipan	1.25
		Persian Clover	*T. resupinatum*	Lightning	1.25
		Phacelia	*P. tanacetifolia*	Unnamed	1
		Plantain	*P. lanceolata*	Captain	1
		Rape	*Brassica napus*	Titan	0.75
		Turnip	*Brassica rapa*	York Globe	0.5
		Leafy Turnip	*Brassica rapa*	Pasja	1
	Conventional	Annual ryegrass	*L. multiflorum*	Devour	25
4	**Regenerative**	Chicory	*Cichorium intybus*	Choice	1
		Cocksfoot	*D. glomerata*	Safin	0.5
		Lucerne	*Medicago sativa*	Takahe	6
		Meadow Fescue	*Festuca pratensis*	Oakdon	4
		Phalaris	*Phalaris aquatica*	Mate	0.3
		Plantain	*P. lanceolata*	Captain	0.5
		Prairie Grass	*B. willdenowii*	Jeronimo	5
		Red Clover	*T. pratense*	Amigain	1
		Subterranean Clover	*T. subterraneum*	Woogenellup	1
		Tall Fescue	*F. arundinceae*	Hummer	4
		Timothy	*Phleum pratense*	WGB23587	2
		White Clover	*Trifolium repens*	Legacy	0.3
	Conventional	Lucerne	*Medicago sativa*	Takahe	15

3.3.2 Grazing

Sheep on conventional plots were at a lower stocking density (77 sheep/ha) compared to the regenerative grazing management (90 sheep/ha), and grazed conventional plots rotationally but were set stock over lambing. Sheep grazed plots rotationally apart from over lambing. On the conventional plots sheep grazed on average three to seven days per plot, and on regenerative plots sheep spent only two to three days in each at a higher stocking density. Exact grazing dates can be found in Appendix A.

3.4 Measurments

3.4.1 Yield and Botanical Composition

Each plot was sampled by the RADE team right before sheep went on and right after it was grazed. Additionally, extra cuts were taken of all plots once a month. Sampling a plot included measurements of forage mass, where an area of a 0.5 m^2 quadrat was cut three times with shearing handpieces. Dividing a plot in three thirds by eye over the long side of the plot, the first cut was taken in the middle section of one short side, repeated in the middle third of the plot and repeated again at the middle of the other short side of the plot. The forage mass of three cuts from one plot was bagged in a seed bag and taken back to the Field Research Centre, where it was weight fresh, mixed thoroughly and a subsample was dried in the oven at 60°C, of 200g for cuts previous to grazing and 100g for cuts after grazing, and another subsample was taken for botanical composition separation. When the subsample in the oven had dried, after approximately 48 hours, the dry matter weight was taken.

Each cut had a subsample put aside for botanical composition analysis, which was done by hand. Each sample was mixed up, divided into quarters and two of the quarters, opposite on a diagonal, were discarded. This process was repeated until the size of the sample was roughly 400 pieces. This sample was sorted into the species that were sown in the specific plot, volunteer white clover, weeds, and dead matter, and then divided into leaf and stem. Everything was placed in small paper bags that were labelled according to plot, species and leaf or stem, and date, and placed into the oven and dried for approximately 48 hours. Each subsample was then weight and a small proportion was kept for near infrared reflectance spectroscopy (NIR) analysis.

3.4.2 Sunscan

Total solar radiation and PAR (photosynthetically active radiation) was sourced from the Broadfield weather station data. A Sunscan was used to measure incident and transmitted PAR over the period of February to July 2023 (Figure 3.5). Sunscan measurements were taken in each plot before it was grazed, and after it was grazed, as well as additional measurements of all plots once a month. Two measurements were taken for each of the three areas over the long axis of a plot, analogously to the quadrant cuts taken, and an average of these six measurements was used as transmitted PAR for a plot at a given date.

SunScan measurements were taken within +/- 2 hours of midday. The sunshine sensor and radio link were set up close to the plots that needed measuring at any given day and four initial calibration measurements were taken, before the first plot was measured. However, the radio link range is limited, and if the sensor had to be moved, another four calibration readings were taken before continuing to measure plots. It was assured that the sensor and the probe were always set up level, and away from any shade.

The sunshine sensor measures direct and diffuse components of light, and the radio link connects the sensor to the SunScan probe over a radius of approximately 100 – 200 meter (Dynamax Inc., n.d.) (Figure 3.6). The SunScan probe has 64 Par sensors within its 1 meter length that allow it to calculate the average light level. The software model used for this calculation takes direct and diffuse incident light, canopy leaf area index, leaf PAR absorption, solar zenith angel, canopy leaf angel distribution, and transmitted fraction into account, and is based on work by Campell (1985) and Norman & Jarvis (1975) (Dynamax Inc., n.d.).

Figure 3.5: Sunshine Sensor (left) and radio link (right) of the SunScan.

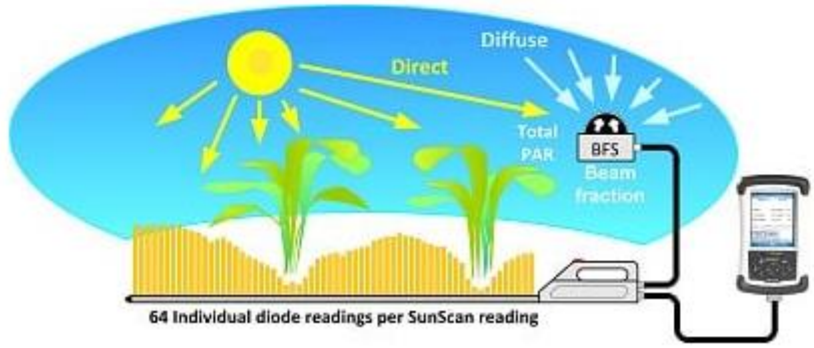

Figure 3.6: SunScan probe. (Delta-T Devices, n.d.)

3.5 Statistical Analysis

Missing pasture mass (kg/ha) data, needed for yield (kg/ha) calculations, was replaced with estimates by adding the observed mass of the same plot closest in time before the missing point (M_1) to the difference of observed pasture mass closest in time after the missing value (M_2) and M_1. That product was divided with the point in time of M_2 (T_2) substracted with the point in time of M_1 (T_1), and then multiplied with the point in time of the predicted value (T_p) substracted with the point of time of M_1. Linear function:

$$Mass_{predicted} = Mass_1 + (Mass_2 - Mass_1) / (T_2 - T_1) * (T_{predicted} - T_1)$$

$Mass_{predicted}$ = Missing point of observed Mass
$Mass_1$ = Observed Mass closest in time before the missing value
$Mass_2$ = Observed Mass closest in time after the missing value
T_1 = Time (Date) of observation of $FIPAR_1$
T_2 = Time (Date) of observation of $FIPAR_2$
$T_{predicted}$ = Time (Date) of observation of $FIPAR_{predicted}$

Missing datapoints for fraction of intercepted PAR were also predicted using a linear equation:

$$FIPAR_{predicted} = FIPAR_1 + (FIPAR_2 - FIPAR_1) / (T_2 - T_1) * (T_{predicted} - T_1)$$

$FIPAR_{predicted}$ = Missing point of fraction of intercepted PAR
$FIPAR_1$ = Observed fraction of intercepted PAR closest in time before the missing value
$FIPAR_2$ = Observed fraction of intercepted PAR closest in time after the missing value
T_1 = Time (Date) of observation of $FIPAR_1$
T_2 = Time (Date) of observation of $FIPAR_2$
$T_{predicted}$ = Time (Date) of observation of $FIPAR_{predicted}$

Linear equation were only possible within growth and defoliation phases. Missing data points of the start or end of a growth or defoliation phase were estimated using an average of the equivalent event in another plot of the same treatment within a latin square as close in time as possible.

Yield (kg/ha) and intercepted PAR (IPAR) (MJ/m^2) were accmuluated over time, starting at the 15th of February until the 28th of June 2023, and weighted by multiplying each value with the size of its plots and dviding by the average size of plots of Latin Saqure (LSQ) one to four. RUE was calculated with the following equation:

$$RUE \quad = Y_a \,/\, IPAR_a$$

Y_a = accumulated yield, starting 15th of Feburary to 28th of June
$IPAR_a$ = accumulated IPAR, starting 15th of Feburary to 28th of June

Units were converted from (kg DM/ha)/(MJ /PAR m^2) to g DM/MJ PAR:

$$RUE\ (g\ DM/MJ\ PAR) \ = \ \mathrm{RUE} \ * \ 1000 \ * \ 1/10\,000$$

To examine differnces between fertility and agricultural system, ANOVAS were run for yield, IPAR and RUE for each date that was an “EXTRA” event (where all plots had measurments of yield and sunscan measurments on the same day), for LSQ one to four combined as well as for each LSQ individually. Extra events were the 15th of February, 15th of March, 12th of April, 17th of May and 28th of June. Weighted data was used only for analysis of combined LSQ data.

Mass data was also weighted for four Latin squares and an ANOVA was run to investigate farmcover at each Extra event over all four LSQs and within each LSQ at the final measurment date (28/06/2023) between the four treatments. An ANOVA was run for post grazing pasture mass between the regnerative and conventional plots. Missing values in LSQ3 for post grazing pasture mass were due to no grazing events ending before the final measurement in the winter grazing plots 45 and 46 and were etimated using the post grazing mass after the official end of the measuring period. A grouped linear regression analysis was run to test for treatment differences in the relationship between recovery of pasture mass against days after defoliation for regenerative and conventional plots. The models were evaluated based on increases in the R2 value over the fitting of a single linear relationship to all the data. Botanical composition was summarized over time in an area graph, for each treatment overall four latin squares and within each latin sqaure, and an ANOVA was run to investigate the differnce between weed and dead content between the two agricultural systems.

Chapter 4

Results

This chapter describes the analysis of effects of agriculture system and phosphorus on radiation use efficiency and its components across the 4.5-month timeframe of the experiment (Objective 3).

4.1 Yield

The average yield of all RA plots was 2347 kg/ha, and the average yield of all CA plots was 3354 kg/ha on the 28th of June. High fertility plots had an average yield of 3000 kg/ha, and the low fertility plots an average of 2702 kg/ha. System was found to have a significant difference in the sum of total yield only on the last two “EXTRA” measurement events, on the 17th of May (p=0.04) and the 28th of June, the end of the measurement period (p=0.007) (Figure 4.1). Differences between fertility levels and system-fertility interaction were found to be non-significant for yield.

The difference in yield accumulation for RA and CA within each individual Latin square was only significant in Latin square 1 on the 12th of April (p=0.024) and in Latin square 3 on the 15th of March (p=0.027) (Figure 4.2). No significant differences were observed between the levels of fertility.

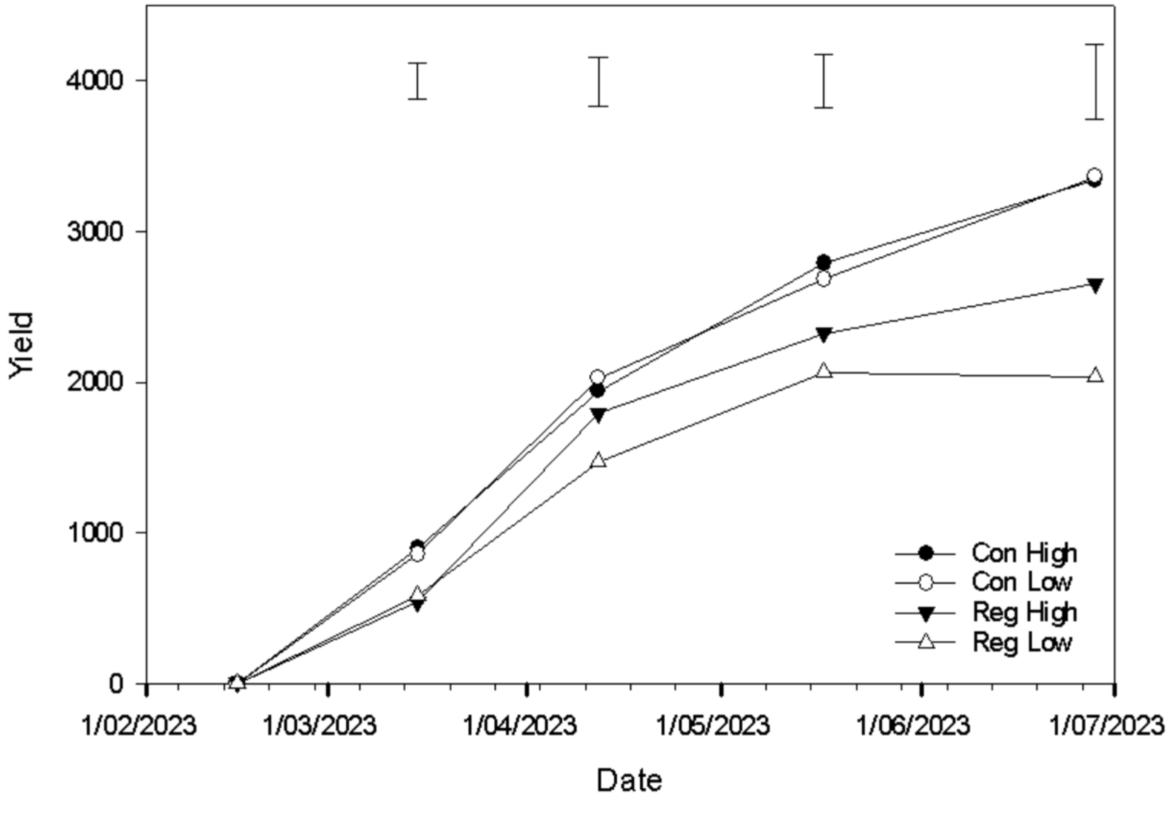

Figure 4.1: The accumulation of yield (kg/ha) per agricultural system (Conventional, Regenerative) at each soil fertility level (Low, High) between the 15th of February and 28th of June.

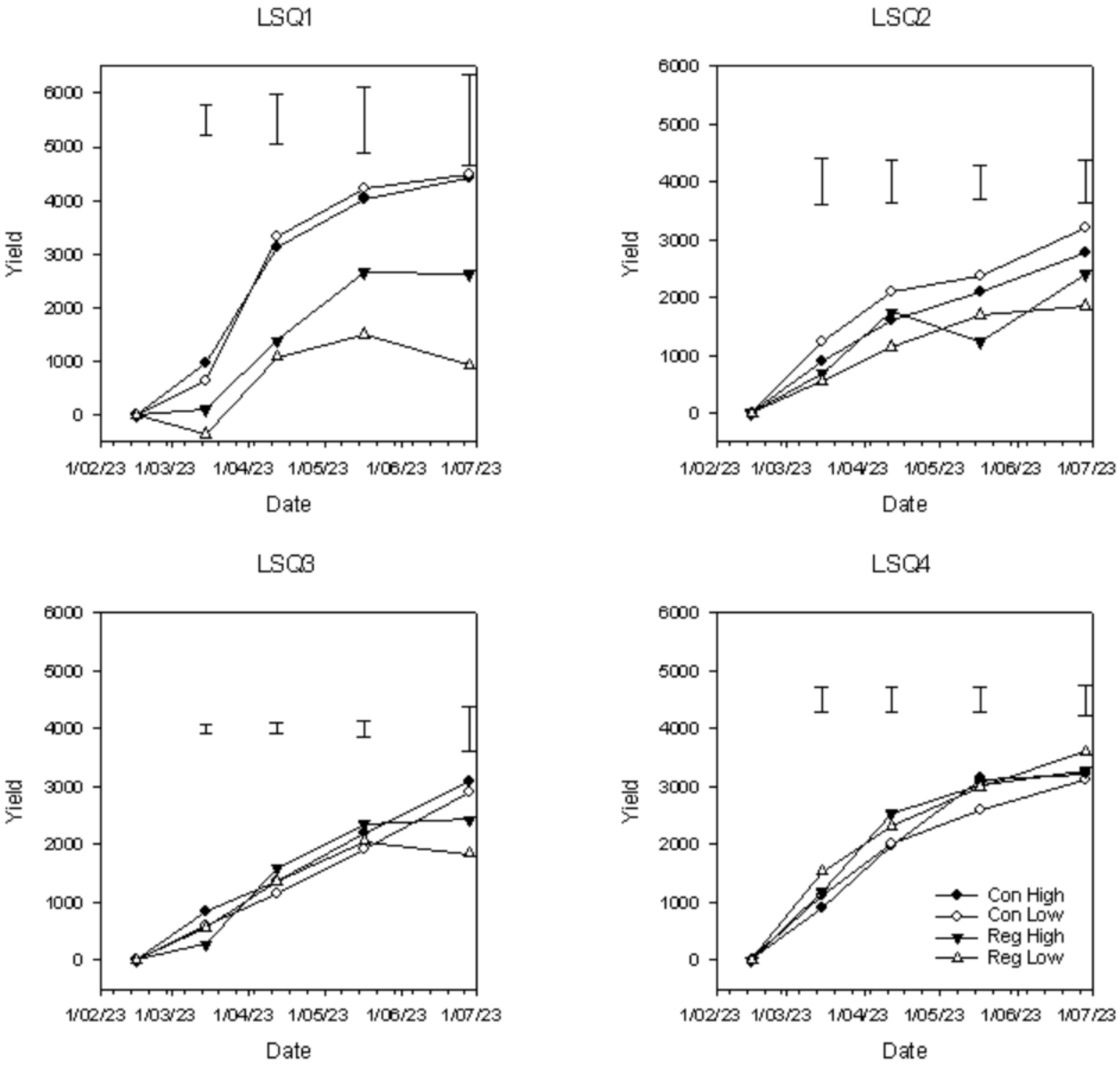

Figure 4.2: Differences in the accumulation of yield (kg/ha) between agricultural systems (Conventional, Regenerative) at each soil fertility level (Low, High) across Latin square one to four.

4.2 Intercepted PAR

The intercepted PAR was found to be significantly different between the two agricultural systems on the 17th of May (p=0.023) and on the 28th of June (p=0.004). The average accumulated intercepted PAR for RA plots was 612 MJ/m^2 and 530 MJ/m^2 for CA plots at the end of the measurement period (Figure 4.3). Differences between fertility levels and system-fertility interaction were found to be non-significant for intercepted PAR. At the level of each individual Latin Square, the only significant difference in IPAR between the two agricultural systems was found in Latin square 2 on the 28th of June (p=0.036) (Figure 4.4).

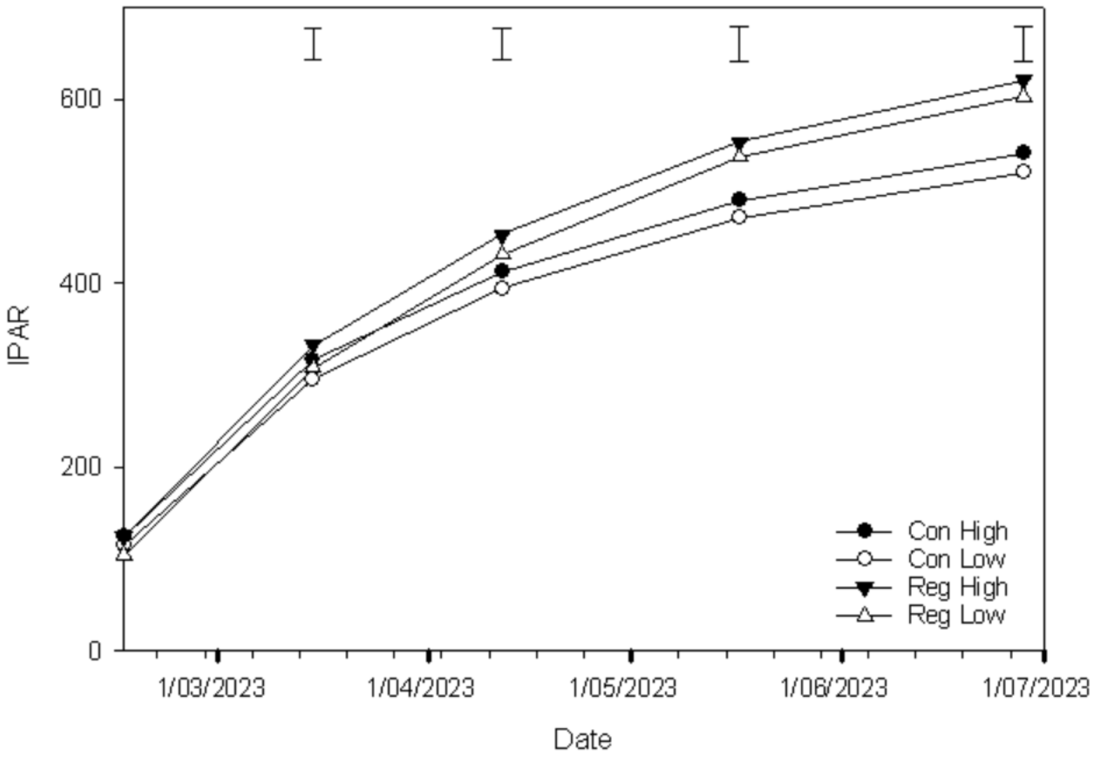

Figure 4.3: Average accumulated intercepted PAR (MJ/m^2) for each agricultural system (RA, CA) over low and high soil fertility from the 15th of February until the 28th of June.

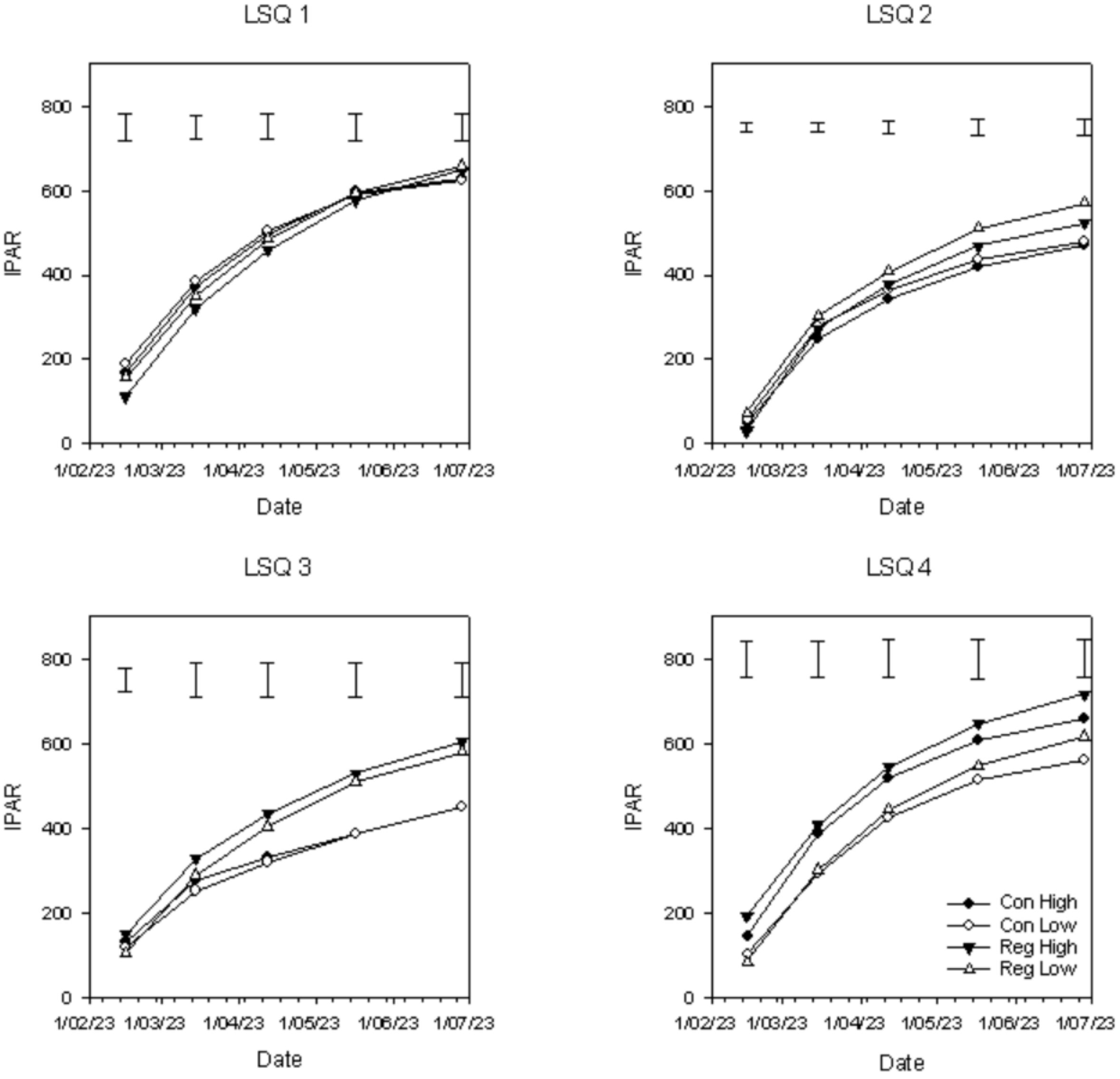

Figure 4.4: Differences in intercepted PAR (MJ/m^2) between agricultural systems (Conventional, Regenerative) at each soil fertility level (Low, High) across Latin square one to four.

4.3 Radiation Use Efficiency

Mean RUE of the regenerative plots across four Latin squares was 0.389 g/MJ, and mean RUE of the conventional plots was 0.646 g/MJ at the end of the measurement period, and 0.534 g/MJ for the high fertility plots and 0.501 g/MJ for the low fertility plots. The difference in RUE between the systems (RA – CA) was found to be highly significant for the 17th of May ($p<0.001$) as well as for the end of the measurement period ($p<0.001$) (Figure 4.5)

At the individual Latin Square level significant differences in RUE between the two agricultural systems were found in Latin square 1 on the 12th of April ($p=0.025$), and in Latin square 3 on the 28th of June ($p=0.018$) (Figure 4.6). The difference in RUE between high and low fertility and the interaction of fertility and system were both found to be non-significant.

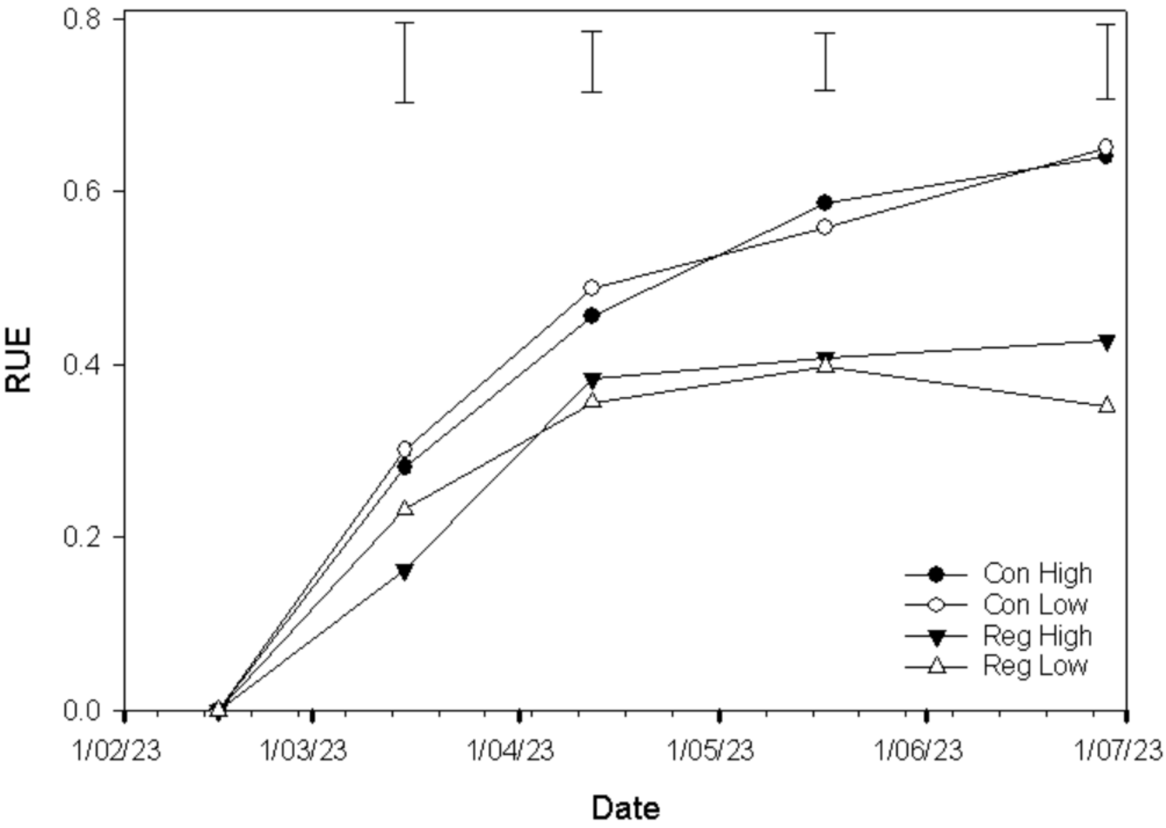

Figure 4.5: Mean radiation use efficiency (RUE) of conventional and regenerative plots at high and low fertility in the RADE.

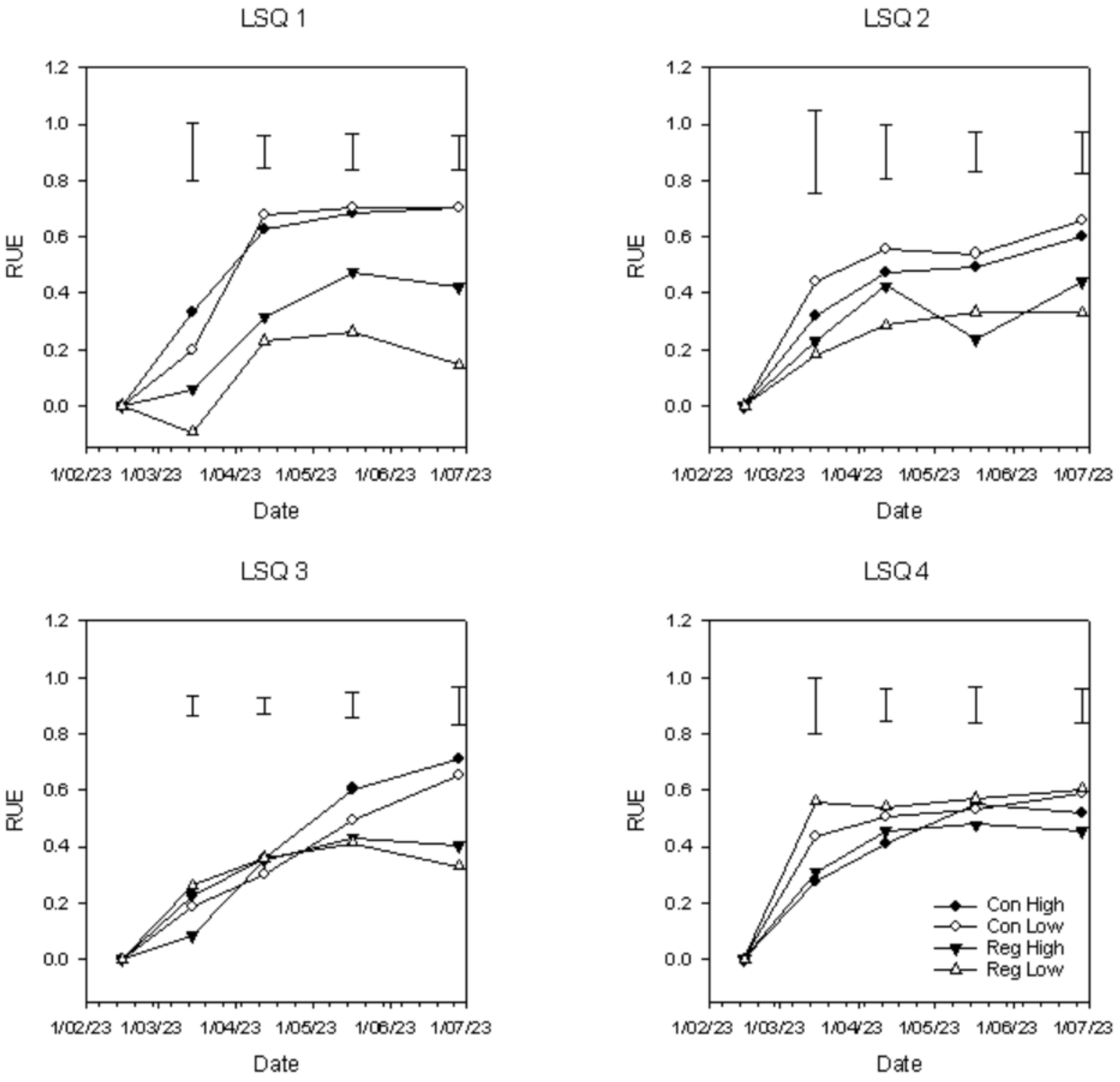

Figure 4.6: Radiation use efficiency of regenerative and conventional plots in the RADE at different levels of soil fertility (High, Low) in Latin Square one to four.

4.4 Farm Cover

The difference in average pasture mass between regenerative and conventional plots (Figure 4.7) was significant at each "extra" measuring event (15/2: p=0.007; 15/3: p<.001; 12/4 p<.001; 17/5: p<.001; 28/6: p<.001). No significant differences were detected at any "extra" event between low and high levels of fertility. At the last day of measurements, the pasture mass of regenerative plots was significantly higher than that of the conventional plots in Latin square 1, 2, and 4, but not in Latin square 3 (Table 4.1). No significant difference in mass between the low and high fertility plots was found.

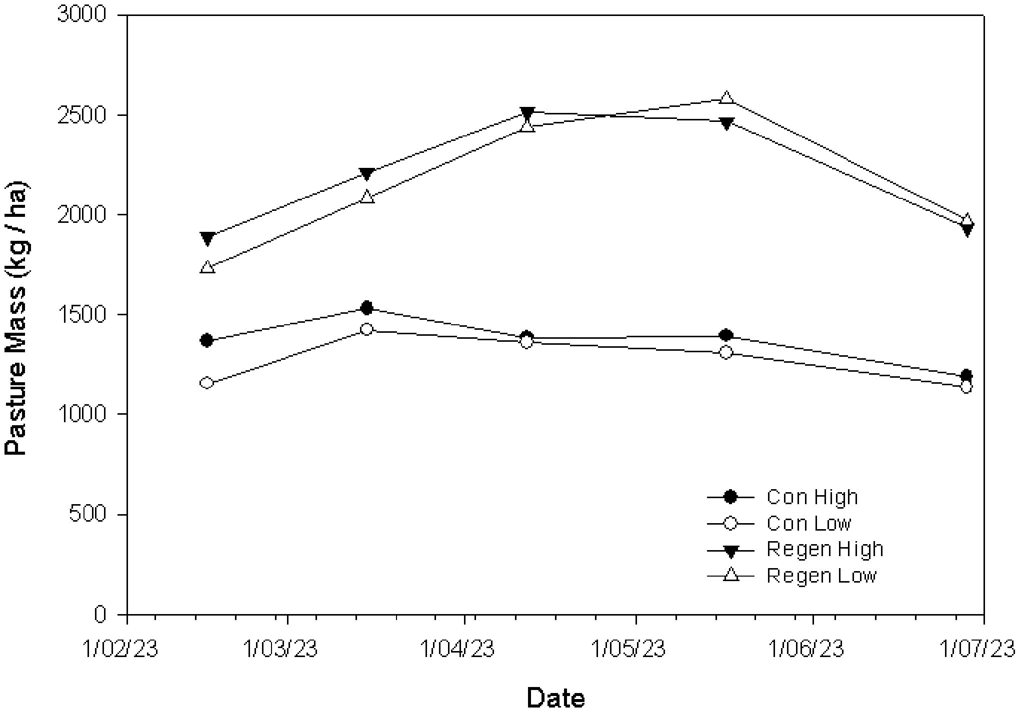

Figure 4.7: Average pasture mass (kg/ha) of conventional and regenerative plots at high and low fertility across Latin square 1 to 4.

Table 4.1: Average pasture mass (kg/ha) of conventional and regenerative plots at high and low fertility within each Latin square.

	Latin Square			
System	**1**	**2**	**3**	**4**
CA	956	973	1404	1186
RA	2262	2065	1502	2196
p value	<.001	0.012	0.736	<.001
SED	76.5	305	279	130

4.5 Post Grazing Pasture Mass

A significant difference was found for post grazing pasture mass between the regenerative at 1809 kg/ha and conventional plots at 866 kg/ha (p<.001) (Figure 4.8). When looking at each individual Latin square (LSQ), the difference between regenerative and conventional plots in post grazing pasture mass was significant in LSQ1, LSQ2, and LSQ4, but not in LSQ3 (Table 4.2).

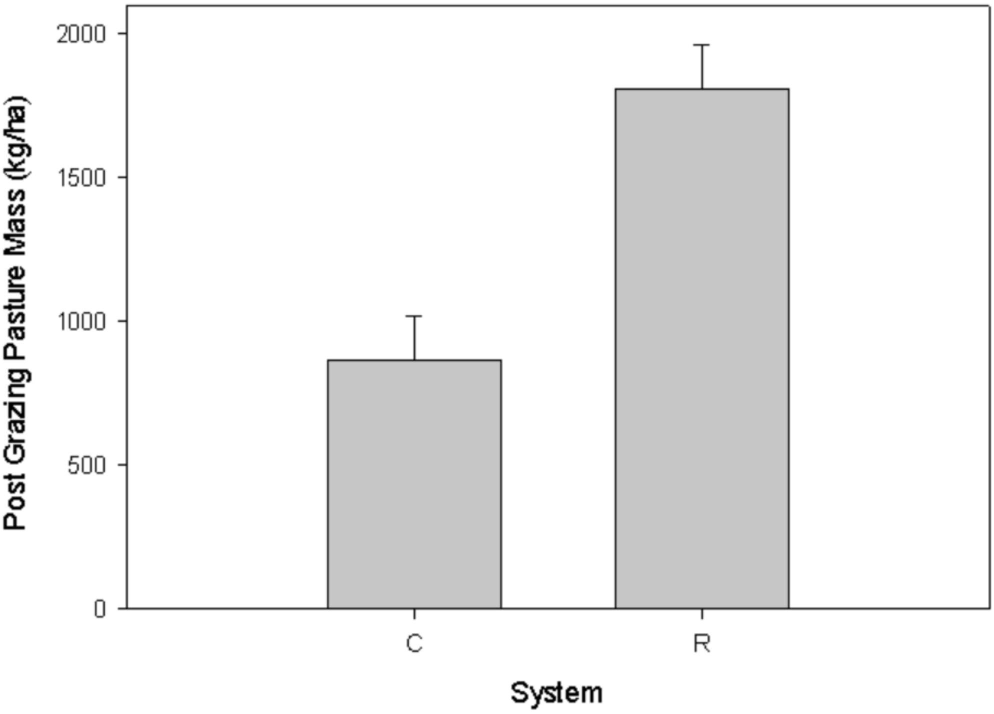

Figure 4.8: Average post grazing pasture mass of conventional and regenerative plots.

Table 4.2: Mean post grazing pasture mass (kg/ha) of each agricultural system per Latin square.

	Latin Square			
System	**1**	**2**	**3**	**4**
CA	1027	820	772	894
RA	2817	2105	1363	1196
p value	<.001	0.003	0.103	0.014
SED	254.4	302.3	320.8	95.7

4.6 Recovery of Pasture Mass after Defoliation

A grouped linear regression between recovery of pasture mass against days after defoliation for each agricultural system showed, a parallel lines relationship increased the R^2 value from 23.9% to 40%. No further improvement was gained by fitting separate lines and intercepts. The parallel lines regression had a common slope which showed growth rate increased at 19.74 kg/ha per day for both systems. However, the y intercept differed between the two systems (p<.001) and the regenerative plots had on average 77.9% more pasture mass on day 0 after defoliation compared to the conventional plots, with an average pasture mass of 1610 kg/ha for the regenerative plots and an average pasture mass of 905 kg/ha for the conventional plots at 0 days after defoliation (Figure 4.9).

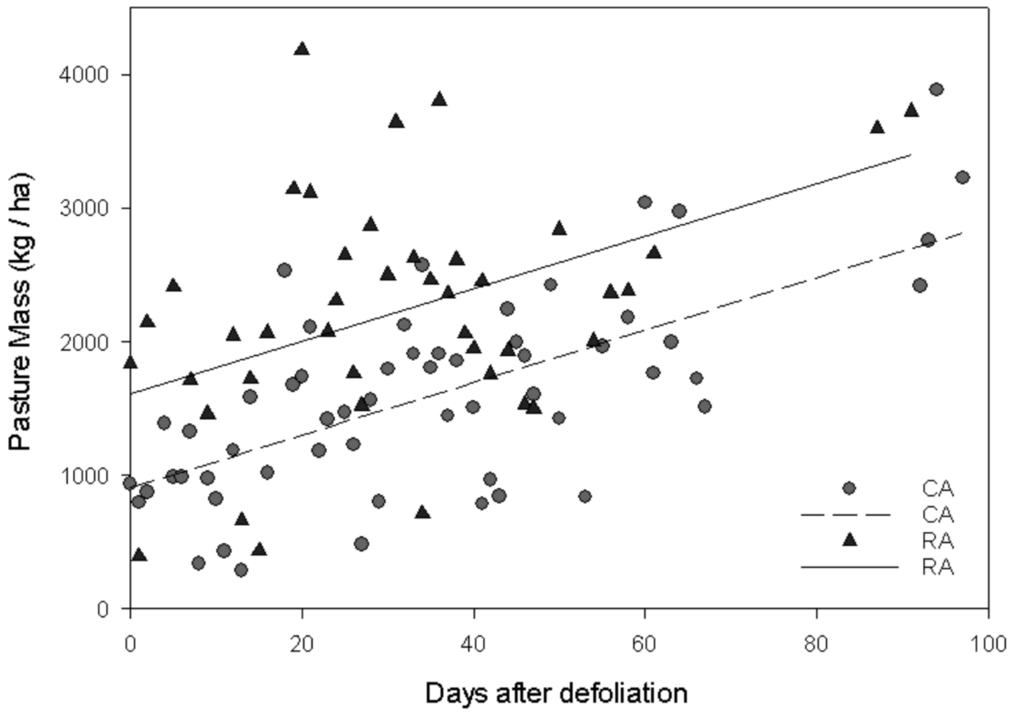

Figure 4.9: Recovery of pasture mass (kg/ha) against days after defoliation of regenerative and conventional plots within Latin squares one to four.

4.7 Botanical Composition

Areas graphs of botanical composition show the contents of each species over time across four Latin squares (Figure 4.10) and within each Latin square (Figure 4.11). ANOVAs comparing the content of dead and weed in regenerative and conventional plots across four Latin squares show a significant difference for both components between the two agricultural systems (Table 4.3).

Table 4.3: Average content of weed and dead material in % across regenerative and conventional pastures.

	Conventional	Regenerative	P value	SED
Dead	0.2420	0.3474	<.001	0.01886
Weed	0.1286	0.0329	<.001	0.01381

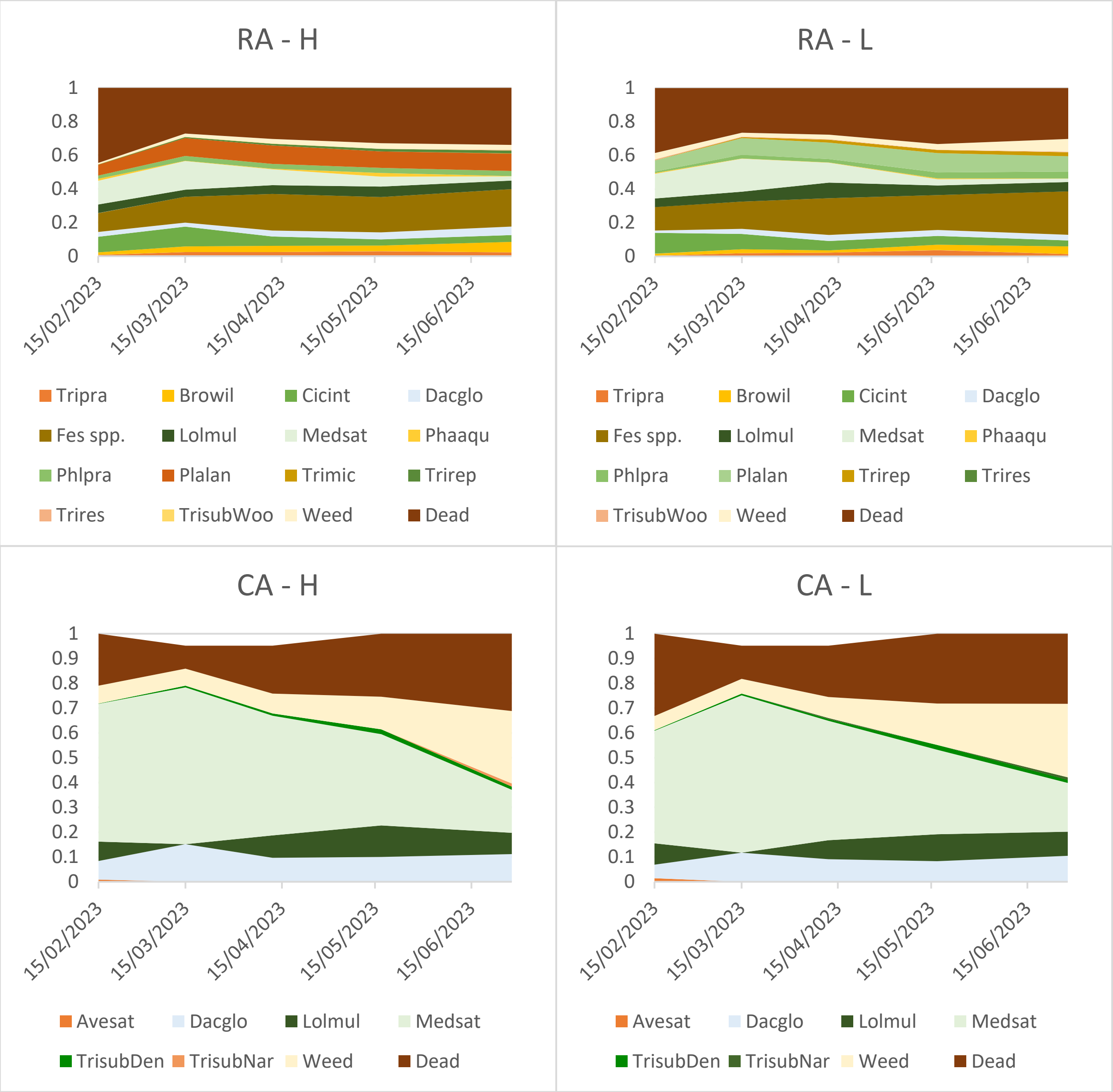

Figure 4.10: Botanical composition of conventional and regenerative plots at high and low level of fertility across four Latin squares.

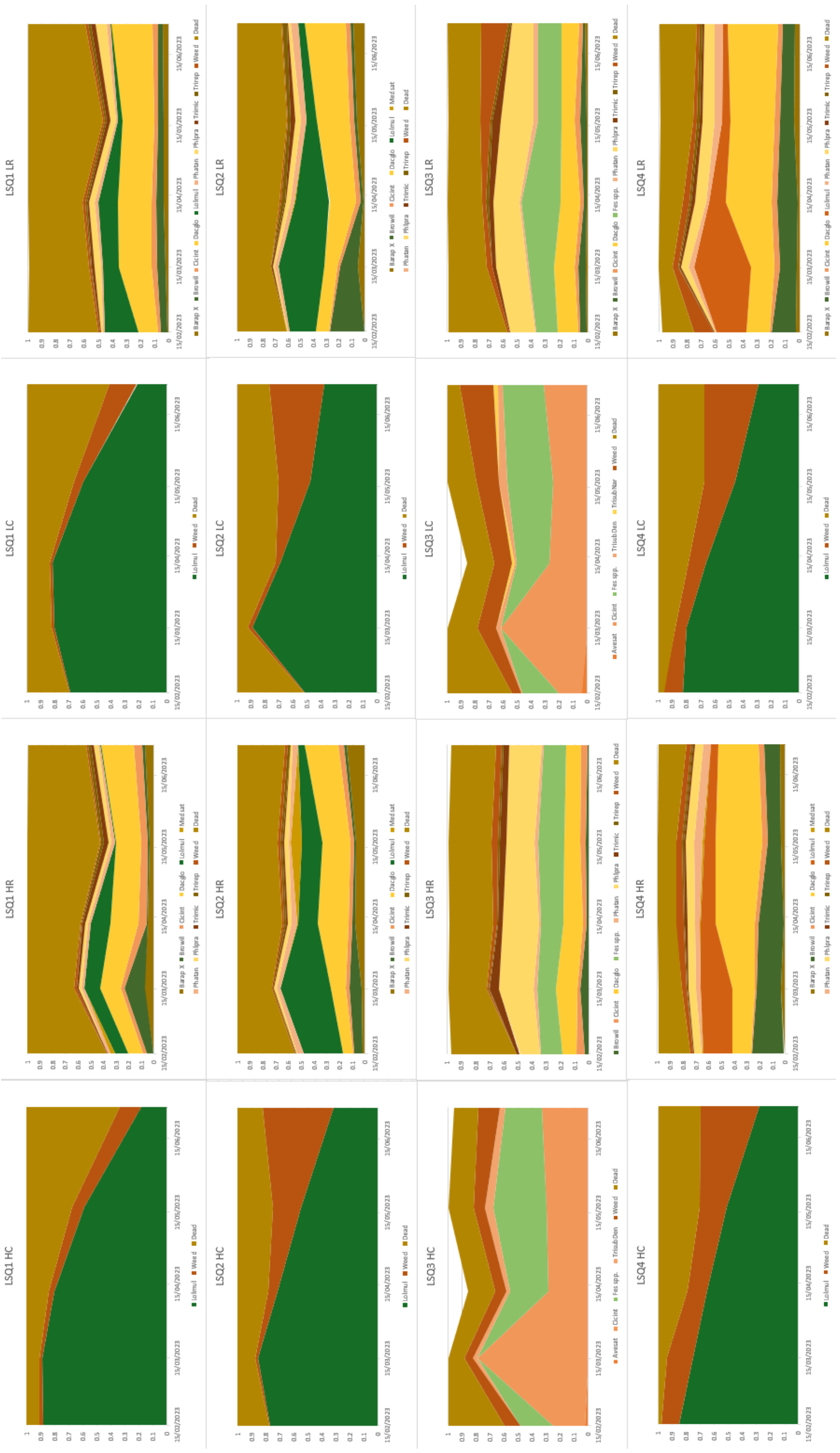

Figure 4.11: Botanical composition of conventional and regenerative plots at high and low level of fertility within each Latin square (1-4).

4.8 Nitrogen Content

Average nitrogen % of pasture dry weight (N%) across both fertility levels (Table 4.4) was significantly different between the two agricultural systems (p<.001). Regenerative pastures had an average N% of 2.44% and conventional pastures had an average of 3.07%. Table 4.5 displays average N% of each system within each Latin square. There was no significant interaction between system and fertility and no significant effect of fertility on N% across all four Latin squares and neither within each Latin square.

Table 4.4: Mean percentage of nitrogen within the pasture of each system, at each level of fertility, across all four Latin squares.

Nitrogen %		**System**	
		Conventional	**Regenerative**
Fertility	**High**	3.13	2.44
	Low	3.02	2.44

Table 4.5: Mean percentage of nitrogen within the pasture of each system within each Latin square (LSQ).

LSQ	**Conventional**	**Regenerative**	**P Value**
1	3.00	2.27	0.005
2	3.61	2.66	<.001
3	2.62	2.30	0.147
4	3.07	2.52	<.001

4.9 NDVI

A linear regression comparing the NDVI data gained from the handheld GreenSeeker had showed an R^2 value of 50.0, indicating that 50% of the observed variation in your Sunscan reading (y axis) is accounted for by GreenSeeker NDVI (x axis). Figure 4.12 depicts the regression line (solid) in comparison to a one to one line (dashed).

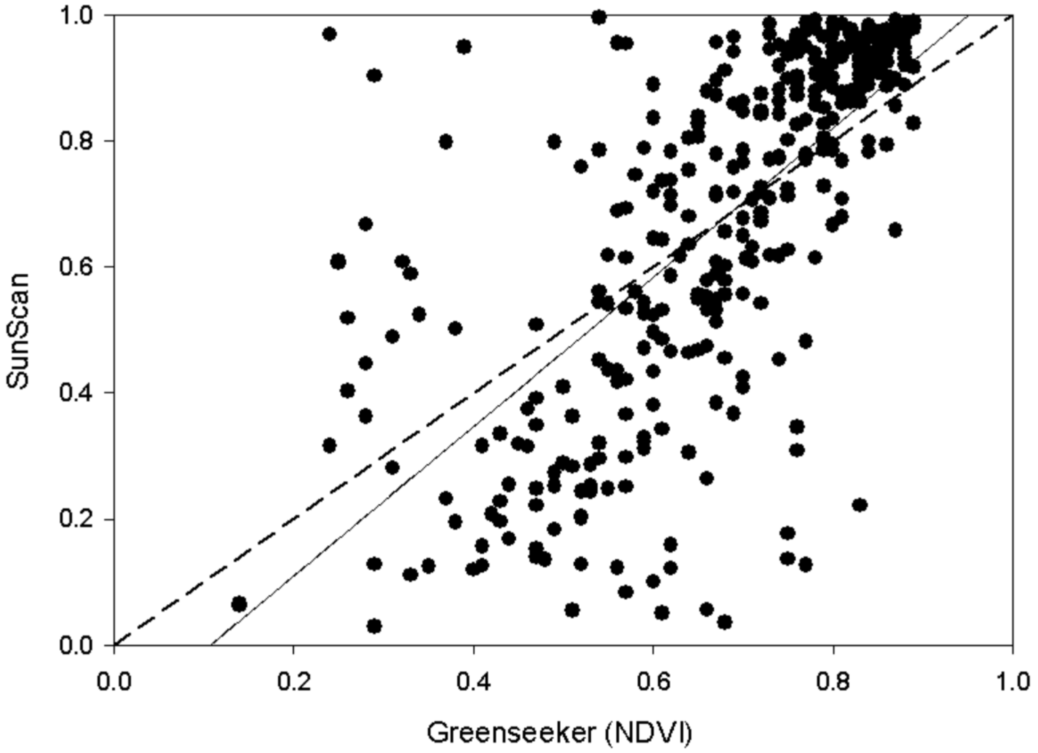

Figure 4.12: Measurments of the handheld Greenseeker in relation to the SunScan measurments.

Chapter 5

Discussion

5.1 Introduction

The aim of this dissertation was to investigate if regenerative agriculture can increase the radiation use efficiency of grassland production (Chapter 1). The review of existing literature (Objective 1, Chapter 2) found no other examinations of radiation use efficiency of grassland production for regenerative agriculture. However, the impacts of principles/practices frequently promoted as part of regenerative agiculture, specifically species-rich pastures, ‘long-rotation’ or ‘lax’ grazing techniques and less chemical fertiliser, on pasture and crop radiation use efficiency were widely understood. Therefore, the dataset collected for this dissertation – from 4.5 months of the new farmlet experiment at Lincoln University (Objective 2, Chapter 3) – appeared to be the first comparison of grassland radiation use efficiency between regenerative and conventional agriculture systems. The analysis of the data (Objective 3, Chapter 4) revealed that radiation use efficiency was 0.26 g DM/MJ PAR lower for the regenerative agriculture system due to 1,007 kg DM/ha less yield and 82 MJ/m^2 more intercepted PAR and therefore did not increase the utilisation of light for grassland production. These results were consistent across the two amounts of phosphorus fertiliser applied.

In this chapter, the results are interpreted in relation to the principles of crop physiology and components of crop radiation use efficiency (Objective 4) and recommendations are made for future research and for the implementation of regenerative agriculture in dry east coast regions of New Zealand.

5.2 Why did regenerative agriculture decrease RUE?

Maximum RUE of pasture is dictated by leaf-level photosynthetic rate under optimum environmental conditions (Turner *et al.*, 2003; Grigera & Oesterheld, 2020). Therefore, it was unexpected that a suboptimal environmental condition being the low fertility plots had no significant impact on RUE compared with the high fertility plots. However, Grigera & Oesterheld (2020) found similar results in their experiment on a mixed grass-legume pasture (Lucerne / Tall Fescue) in Argentina. They found that the average annual RUE of the non-fertilized irrigated pasture (1.34 g/MJ) was not significantly different from the fertilized (diammonium phosphate and urea) irrigated pasture (1.42 g/MJ).

There is a linear relationship between the amount of dry matter that is produced, and the amount of solar radiation intercepted by a pasture (Ullah *et al.*, 2019). In the RADE, at the end of the measuring period of the dissertation, RA plots had produced significantly less yield at 2347 kg/ha than CA plots at 3354 kg/ha (p=0.007), but intercepted significantly more PAR, 612 MJ/m^2 compared to 530 MJ/m^2 CA plots (p=0.004). To investigate those differences, the effect of the different grazing rotations and the different pasture types was examined further.

One of the major differences in management between the regenerative and the conventional plots in this experiment was the higher stocking density and shorter time spent in each plot for sheep grazing the regenerative plots. This resulted in a higher average farm cover (p<0.05 for entire period of measurements) (Figure 4.7), a higher post grazing pasture mass (p<.001) (Figure 4.8) and therefore pasture recovery started with a higher pasture mass for the regenerative plots compared to the conventional plots, but there was no difference in rate of recovery of pasture mass (Figure 4.9).

Blanco *et al.* (2020) studied the radiation use efficiency of the herbaceous layer in woodlands and shrublands and its association with different grazing regimes, a moderate rotational grazing regime with 15 animal units/ha/year and a severe continuous grazing regime with a stocking rate greater than 10 animal units/ha/year. They found that radiation use efficiency (g/MJ) was higher (p<0.05) under a moderate intense grazing regime (0.508) than under a server grazing regime (0.181). Both agricultural systems on the RADE use a rotational grazing regime, and Blanco *et al.* (2020) "severe grazing regime" would be hard to compare to either of these. However, their "moderate grazing regime" is possibly comparable to the grazing of the conventional plots in the rate, as they had an average stocking rate of 77 sheep/ha which, with a sheep being considered approximately 0.2 animal units (Redfearn & Bidwell, 2017), is the equivalent to about 15.4 animal units. With the radiation use efficiency being greatest for the moderate grazing regime for Blanco *et al.* (2020) and also for the conventional grazing regime in the RADE, and with a decrease being observed in both, the more severe, set stocking grazing regime as well as the long rotation, high stocking density grazing regime of the regenerative management in the RADE, it shows that the conventional grazing rotation is operating at a near optimum.

The consistently higher farm cover of the plots under regenerative management enabled it to intercept more light compared to the conventional plots. However, the percentage of dead material within the regenerative pasture (35%) was higher (p<.001) than in the conventional pasture (24%). This was not surprising, as it is widely known, that grazing down to a lower residual encourages vegetative growth, and leaving more residual after grazing will lead to accumulation of reproductive stems that livestock have avoided to consume, and those left over stems subsequently die (Korte *et al.*, 1982). However, even though the percentage of dead was higher within the regenerative plots, intercepted PAR was still higher. This can possibly be described to the consistently higher pasture mass of the regenerative pasture, and therefore higher leaf area index (LAI) to still have more photosynthetically active vegetation.

Furthermore, as Brougham (1958) points out, light interception of a pasture is influenced by its architecture and make up. When comparing monoculture ryegrass and white clover and a mixed ryegrass / white clover pasture, he found that the mixed sward intercepted 95% of light at an LAI of 4.5, where as the ryegrass monoculture required an LAI of 7.1 and the clover pasture an LAI of 3.5 in order to intercept 95% of light. Therefore the lucerne monoculture stand of the conventional plots would have been expected to intercept light more efficiently at a lower farm cover compared to the mixed species pastures of the regenerative plots. However, this was not seed in the data of this dissertation.

A factor that could have possibly decreased light interception of the conventional plots is the fact that not every Latin square had lucerne monocultures as the conventional pasture type, but instead Latin square 3 had a grass/clover based pasture as well as annual ryegrass winterfeed. This was visible when comparing the accumulated light interception of the individual Latin squares, it can be seen that Latin square 3 had accumulated less PAR than Latin square 1 and 4. However, light interception in Latin square 2, where conventional pastures also consisted of lucerne monocultures, did not match that pattern. Figure 4.12 shows the high weed content of the conventional pastures in Latin square 2, especially in comparison with Latin square 1. Additionally there was a significantly higher ($p<.001$) amount of weed content in all the combined conventional pastures (13%) when compared to the regenerative pastures (3%). Weed content could have had a negative impact on light interception, as they compete with the pasture for resources such as light (Ghanizadeh & Harrington, 2019).

Post grazing pasture mass was higher in the regenerative plots compared to the conventional ($p<.001$) and at the same time radiation use efficiency was lower for the regenerative plots compared to the conventional $p<0.001$). This result is consistent with the findings presented by Grigera & Oesterheld (2020). Grigera & Oesterheld (2020) conducted an experiment on forage productivity of a mixed grass-legume pasture (lucerne / tall fescue) and investigated radiation use efficiency in relation to two different severities of simulated (mown) defoliation (less severe to 15cm and severe to 7cm). They found that, even though the fraction of absorbed PAR was greater for the less severe defoliation treatment over the whole year, there were no significant differences in RUE in Summer, Autumn, and Winter. Only in summer they observed a significantly higher radiation use efficiency for the more severe defoliation treatment. However, the overall radiation use efficiency of the severe defoliation (1.41 g/MJ) was still significantly higher than that of the less severe defoliation treatment (1.24 g/MJ) ($p<0.05$). They concluded that severe defoliation at any season significantly reduced the fraction of absorbed PAR and increased RUE. However, less severe defoliation, as in the management of the regenerative plots on the RADE could still have implication on soil carbon that need further evaluation.

Additionally, Nitrogen content was significantly lower in the regenerative pastures (2.44%) compared to the conventional pastures (3.07%) ($p<.001$). This was also seen at the individual Latin square level within Latin square 1, 2, and 4, but not in Latin square 3. Latin square 3 is different to 1, 2, and 4 in terms of the conventional pasture type being Cocksfoot / Sub clover and two of the conventional plots had been converted into a winter feed crop of annual ryegrass over the period of this dissertation. The pasture type of the conventional plots within Latin squares 1, 2, and 4 was lucerne monoculture.

Those results were therefore not surprising, as lucerne is known to have a higher N% compared to grasses (Mills & Moot, 2010). Interestingly, these results did not completely translate to the RUE of the Latins squares, with a significant difference of RUE between systems found in Latin square 1 on the 12th of April ($p=0.025$) but not at the end of the measurement period, and not in Latin square 2 or 4 at any date. However, there was a significant difference in RUE between the two systems in Latin square 3 at the end of the measuring period ($p=0.018$) (Figure 6). Therefore, the nitrogen content of each pasture type was not considered to be a key influence on RUE over the measurement period of this dissertation.

Sinclair & Horie (1989), building on the work of Monteith (1977), have shown, that Leaf N has an influence on RUE of maize, rice, and soybean, with an increase in RUE with increasing leaf N content. However, they have also found that with increasing leaf N content, RUE will reach a near maximum and only little response in RUE is expected after a certain leaf N level. They also point out that there are differences between species in RUE response to leaf N, with soybean having the highest requirement for leaf N to reach a near maximum RUE. This might have had an influence on the little response of RUE to N% of pasture within the RADE, with the lucerne monoculture having a higher N% in general, but possibly also a higher requirement for N% to reach its near maximum RUE, and the grasses although having less N%, having also a lower N% requirement to reach near maximum RUE. The results from Latin square 3 in terms of no significant difference in N% between systems but a significant difference in RUE open an opportunity for further research, in terms of what has influenced the difference in RUE.

5.3 Why did amount of phosphorus not affect RUE?

The effect of two different levels of soil fertility within both systems and an interaction between soil fertility and agricultural system were investigated. No significant interaction between soil fertility and agricultural system was observed for neither yield, or intercepted PAR, or RUE ($p>0.05$), and no significant difference was observed between the high and low soil fertility plots for any of these factors either ($p>0.05$), over the period of this dissertation. This was constant on the combined four Latin squares as well as at each individual Latin square. Therefore, it is assumed that soil fertility levels did not influence the difference in RUE between the two agricultural systems, and the focus should be shifted to other explanatory factors, such as pasture type and composition, and the influence of the two different grazing regimes. However, the measurement period of this dissertation was at the end of the first year after establishment of the RADE, and it will be interesting to see if effects of soil fertility are more prominent within the following years of the six year experiment.

Soil test values from November 2021 differentiating between high and low fertility plots were available for Latin square1 and 2, with the Olsan P (ug/ml) sitting at 8 for the low fertility plots in both Latin squares and at 15 for high fertility plots in Latin square 1 and at 10 for Latin square 2. Fertiliser applications of Sulphur Super 20 followed at the end of November / the start of December in Latin square 1 and 2, and Superphosphate followed in March 2022 in Latin square 3 and 4. The actual aim of fertility difference is an Olsen P of 10 for the low fertility plots and an Olsen P of 20 for the high fertility plots. However, the actual difference between low and high fertility plots might have been less than intended, which could have had an effect on the non-significant results of differences in RUE between high and low fertility plots.

5.4 SunScan in comparison to NDVI measurements of the GreenSeeker

The measurements of the SunScan have the disadvantage that they are time intensive. Measuring all 64 plots in one day took on average about five to six hours. In addition to that, there were several technical issues that prevented data collection on these days. SunScan measurements also assume that all pasture mass intercepts light, and does not differentiate between green herbage and dead material. An alternative method of measuring light interception could be to use the GreenSeeker, a handheld sensor that measures normalized difference vegetation index (NDVI). Therefore the correlation between intercepted PAR (SunScan) and NDVI was analysed. The linear regression provided an R^2 value of 50.0, indicating that only 50% of the observed variation in your Sunscan reading is accounted for by GreenSeeker NDVI, and the accuracy to use the data obtained by the GreenSeeker to estimate light interception would be unreliable. However, further research into the relationships between these two factors within the individual pasture types could increase the accuracy of predictions based on the GreenSeeker. Pellegrini *et al.* (2020) compared two different methods to measure NDVI (Sentinel-2 and GreenSeeker) to the SunScan in wheat crops and found that the Sentinel-2 (images from two satellites) was more suitable to estimate light interception, but that the GreenSeeker was suitable to fill in for gaps under cloudy conditions.

5.5 Limitations

One of the key limitations of this dissertation was the low reliability on the SunScan, as there were more than several occasions were the SunScan would come up with an error message and would not take measurements anymore. The field technician at the Lincoln University Field Research Centre was consulted in these cases when possible. However, this was dependant on the availability of the technician paired with the fact that some measurements were taken on weekends. In most of these cases no measurements were possible with the SunScan at all, or if after a keen amount of effort and trying measurements were collected by the SunScan, the data that was collected from these days proved to be immensely different from days of data collection were no technical issues occurred. Some of the data indicated that the plants were emitting light, which was considered to be not possible by the author. Therefore even if data collection was possible on days with technical issues, it was not used in the data analysis. This caused larger gaps in the data as initially expected.

Another limitation of, not only this dissertation but also previous and further research on regenerative agriculture, is the absence of a universal scientific definition of the term “Regenerative Agriculture”. This can result in differing interpretations of the rather novel agricultural system and lead to challenges for researchers. Depending on the interpretation of each individual researcher the implications of regenerative agricultural studies and the suitability of the agricultural system to a certain farming environment might change.

5.6 Reccomendations for implication

As most New Zealand farming systems are based on best practice which relies on scientific knowledge, many practices from regenerative agriculture are already implemented. For example most pastures aren’t monocultures, but instead based on ryegrass and white clover in areas that are not drought prone or are irrigated, or for drought prone areas are based on a grass/clover mix that includes more drought prone species such as tall fescue or cocksfoot, and red clover or subterranean clover. However, the multispecies pastures as present in the RADE including up to twelve different species are not widely used. Including more than only one grass and one clover is unlikely to lift the yield of pastures further, but instead could provide farmers with a higher stability of yield, as different species will adapt differently to environmental changes. This could be beneficial to farmers in dry east coast regions of New Zealand, that regularly experience drought and at the same time have had to cope with extreme rainfall events within the last two years.

Benefits of minimum tillage are already widely accepted in New Zealand and often implemented under the right circumstances. However, to prepare a paddock for direct drilling usually involves the spraying of herbicide. Further research would be required that compares the drilling practices into sprayed pastures compared to directly into old pastures that were only grazed hard, before recommendations to farmers can be made.

Based on the difference in yield the rotational grazing regime based on conventional best practice would be recommended over the regenerative adaptive grazing method. However, as with the multispecies pastures, the regenerative grazing regime could have the potential to have a more stable yield (but lower), and due to the high residual some of the vegetation can possibly build up a seedbank which could be beneficial in high stress environments, such as the dry east coast region. However, the feasibility of that can be questioned and no recommendations should be made without further research.

5.7 Recommendations for further research:

Further research will be required to investigate the implications of the regenerative agricultural system and its associated limited radiation use efficiency on animal live weight gains as well as on soil carbon sequestration, as this dissertations focus has laid solely on pasture production. Additionally, there is an opportunity for further research within the RADE on radiation use efficiency during the following years of the experiment, as the botanical composition of the multispecies pastures is expected to change, which can likely have an effect on the radiation use efficiency. Furthermore, measurements of specific leaf area of each species could be taken, to delve even deeper into radiation use efficiency of the regenerative and conventional pastures in the RADE.

5.8 Conclusion

Radiation use efficiency was found to be significantly lower within the plots of the RADE that were under regenerative farm management compared to the plots under conventional management. Therefore the results of this dissertation were inconsistent with the objective, that regenerative agricultural pastures were expected to have a higher radiation use efficiency. However, there has been only very limited research on the radiation use efficiency of this novel agricultural system, so further research is required to replicate these observations. No significant difference in radiation use efficiency were observed between the two levels of fertility.

The higher radiation use efficiency of the conventionally farmed plots in the RADE give rise to the hypothesis that the rotational grazing system typically found in New Zealand agriculture is operating at a near optimum and cannot be compared to most livestock systems within other countries, and in this authors opinion, is already a regenerative system in itself.

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Appendix A

Grazing dates

Table A: Dates for shifting of sheep for Latin squares (LSQ) 1 – 4 from the 15th of February until the 28th of June. Empty cells indicate that sheep were either already in the paddocks of the start of the measuring period or still in the paddock at the end of a measuring paddock.

LSQ	Plot	Sheep in	Sheep Out
1	1		15/02/2023
	1	20/03/2023	27/03/2023
	1	12/05/2023	19/05/2023
	2	3/03/2023	6/03/2023
	2	3/04/2023	5/04/2023
	2	10/05/2023	12/05/2023
	3		17/02/2023
	3	17/03/2023	24/03/2023
	3	9/05/2023	16/05/2023
	4	6/03/2023	8/03/2023
	4	5/04/2023	7/04/2023
	4	12/05/2023	15/05/2023
	5	17/02/2023	20/02/2023
	5	24/03/2023	31/03/2023
	5	16/05/2023	24/05/2023
	6	8/03/2023	10/03/2023
	6	7/04/2023	10/04/2023
	6	15/05/2023	18/05/2023
	7	15/02/2023	23/02/2023
	7	27/03/2023	3/04/2023
	7	19/05/2023	26/05/2023
	8	6/03/2023	8/03/2023
	8	5/04/2023	7/04/2023
	8	12/05/2023	15/05/2023
	9	10/03/2023	13/03/2023
	9	10/04/2023	12/04/2023
	9	18/05/2023	20/05/2023
	10	23/02/2023	1/03/2023
	10	3/04/2023	10/04/2023
	10	26/05/2023	2/06/2023
	11	8/03/2023	10/03/2023
	11	7/04/2023	10/04/2023
	11	15/05/2023	18/05/2023
	12	20/02/2023	25/02/2023
	12	31/03/2023	7/04/2023
	12	24/05/2023	31/05/2023
	13	10/03/2023	13/03/2023
	13	10/04/2023	12/04/2023
	13	18/05/2023	20/05/2023

	14	25/02/2023	3/03/2023
	14	7/04/2023	14/04/2023
	14	31/05/2023	6/06/2023
	15	13/03/2023	15/03/2023
	15	12/04/2023	14/04/2023
	15	20/05/2023	22/05/2023
	16	1/03/2023	6/03/2023
	16	10/04/2023	17/04/2023
	16	2/06/2023	8/06/2023
2	17	6/03/2023	13/03/2023
	17	17/04/2023	24/04/2023
	17	8/06/2023	14/06/2023
	18	3/03/2023	10/03/2023
	18	14/04/2023	21/04/2023
	18	6/06/2023	12/06/2023
	19	13/03/2023	15/03/2023
	19	12/04/2023	14/04/2023
	19	20/05/2023	22/05/2023
	20	17/03/2023	20/03/2023
	20	14/04/2023	17/04/2023
	20	22/05/2023	24/05/2023
	21	17/03/2023	20/03/2023
	21	14/04/2023	17/04/2023
	21	22/05/2023	24/05/2023
	22	20/03/2023	22/03/2023
	22	17/04/2023	19/04/2023
	22	24/05/2023	26/05/2023
	23	13/03/2023	20/03/2023
	23	24/04/2023	1/05/2023
	23	14/06/2023	19/06/2023
	24	10/03/2023	17/03/2023
	24	21/04/2023	28/04/2023
	24	12/06/2023	17/06/2023
	25	19/04/2023	21/04/2023
	25	26/05/2023	29/05/2023
	26	17/04/2023	19/04/2023
	26	24/05/2023	26/05/2023
	27	28/04/2023	4/05/2023
	28	1/05/2023	6/05/2023
	29	4/05/2023	9/05/2023
	30	6/05/2023	12/05/2023
	31	21/04/2023	24/04/2023
	31	29/05/2023	2/06/2023
	32	19/04/2023	21/04/2023
	32	26/05/2023	29/05/2023
			15/02/2023
3	33	22/03/2023	24/03/2023
	33	24/04/2023	26/04/2023
	33	2/06/2023	8/06/2023
	34	17/03/2023	29/03/2023

	34	17/04/2023	26/04/2023
	34	26/05/2023	10/06/2023
	35	20/03/2023	22/03/2023
	35	21/04/2023	24/04/2023
	35	29/05/2023	4/06/2023
	36	17/03/2023	29/03/2023
	36	17/04/2023	26/04/2023
	36	26/05/2023	7/06/2023
	37	24/03/2023	3/04/2023
	37	26/04/2023	5/05/2023
	37	7/06/2023	18/06/2023
	38	22/03/2023	24/03/2023
	38	24/04/2023	26/04/2023
	38	4/06/2023	12/06/2023
	39	24/03/2023	5/04/2023
	39	26/04/2023	5/05/2023
	39	10/06/2023	22/06/2023
	40	15/02/2023	17/02/2023
	40	24/03/2023	27/03/2023
	40	26/04/2023	28/04/2023
	40	8/06/2023	16/06/2023
	41	27/02/2023	28/02/2023
	41	15/03/2023	16/03/2023
	41	5/05/2023	10/05/2023
	41	12/06/2023	21/06/2023
	42	27/02/2023	28/02/2023
	42	15/03/2023	16/03/2023
	42	5/05/2023	10/05/2023
	42	16/06/2023	26/06/2023
	43	18/06/2023	28/06/2023
	44	22/06/2023	
	45	17/06/2023	
	46	19/06/2023	
	47	28/02/2023	2/03/2023
	47	16/03/2023	17/03/2023
	47	16/06/2023	
	48	28/02/2023	2/03/2023
	48	16/03/2023	17/03/2023
	48	12/06/2023	
			17/02/2023
4	49	10/03/2023	17/03/2023
	49	5/05/2023	12/05/2023
			17/02/2023
	50	10/03/2023	17/03/2023
	50	5/05/2023	12/05/2023
	50	28/06/2023	
	51	17/02/2023	20/02/2023
	51	27/03/2023	29/03/2023
	51	28/04/2023	1/05/2023
	51	26/06/2023	

		15/02/2023
52	24/03/2023	27/03/2023
52	26/04/2023	28/04/2023
52	21/06/2023	28/06/2023
53	15/02/2023	17/02/2023
53	27/03/2023	29/03/2023
53	28/04/2023	1/05/2023
53	28/06/2023	
54	20/02/2023	22/02/2023
54	29/03/2023	31/03/2023
54	1/05/2023	3/05/2023
55	17/02/2023	24/02/2023
55	29/03/2023	5/04/2023
55	12/05/2023	17/05/2023
56	17/02/2023	24/02/2023
56	29/03/2023	5/04/2023
56	12/05/2023	17/05/2023
57	22/02/2023	24/02/2023
57	31/03/2023	3/04/2023
57	3/05/2023	5/05/2023
58	17/02/2023	20/02/2023
58	29/03/2023	31/03/2023
58	1/05/2023	3/05/2023
59	24/02/2023	3/03/2023
59	5/04/2023	11/04/2023
59	17/05/2023	22/05/2023
60	24/02/2023	3/03/2023
60	5/04/2023	11/04/2023
60	17/05/2023	22/05/2023
61	3/03/2023	10/03/2023
61	11/04/2023	17/04/2023
61	22/05/2023	26/05/2023
62	3/03/2023	10/03/2023
62	11/04/2023	17/04/2023
62	22/05/2023	26/05/2023
63	20/02/2023	22/02/2023
63	31/03/2023	3/04/2023
63	3/05/2023	5/05/2023
64	24/02/2023	27/02/2023
64	3/04/2023	5/04/2023
64	10/05/2023	12/05/2023